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## METALLURGICAL ABSTRACTS

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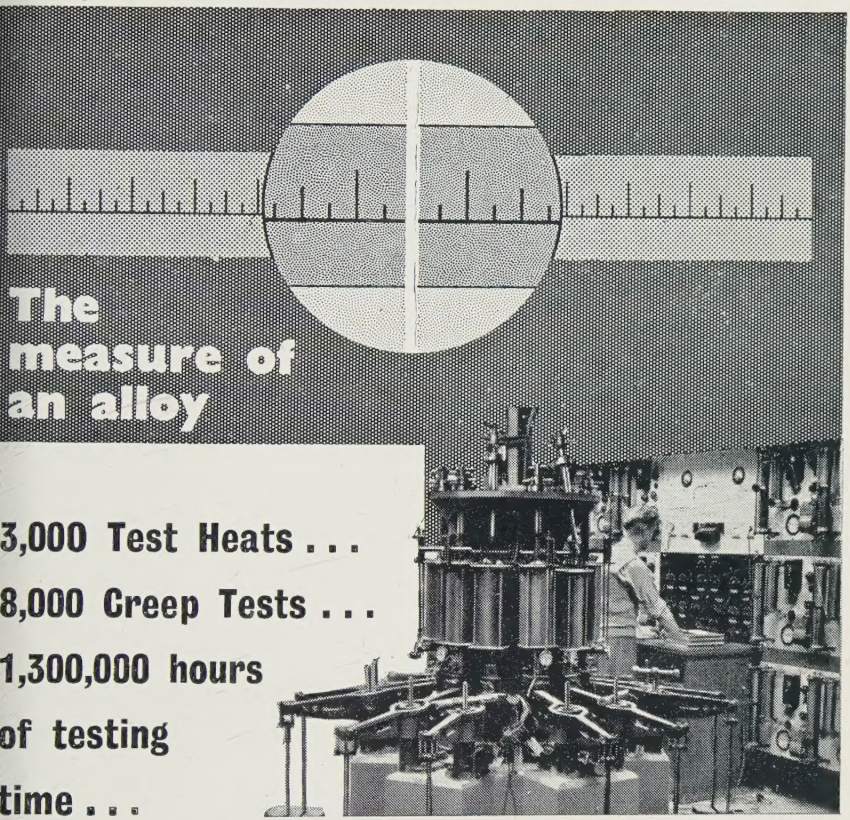
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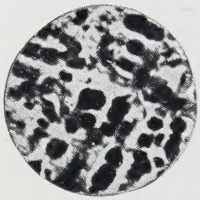
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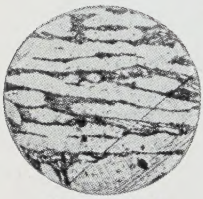
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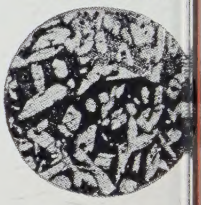


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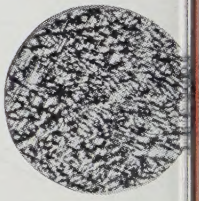
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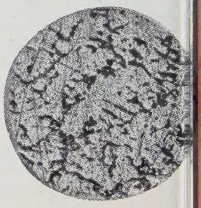
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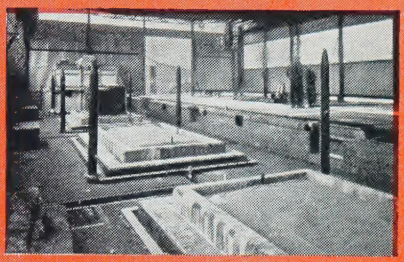
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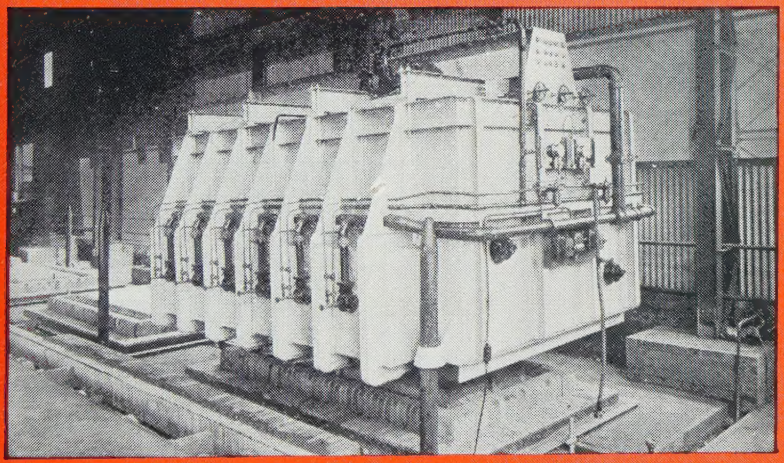
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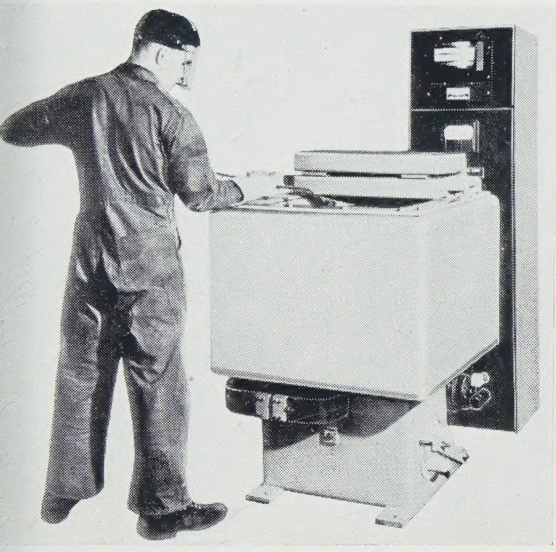
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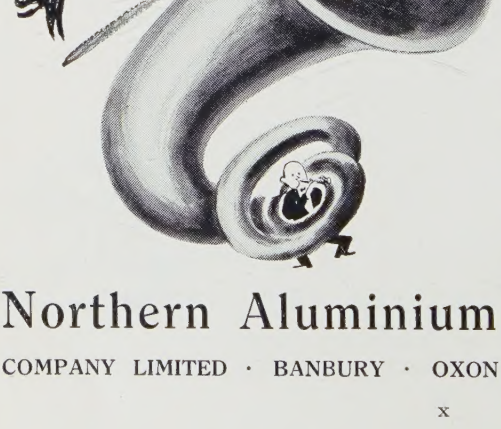
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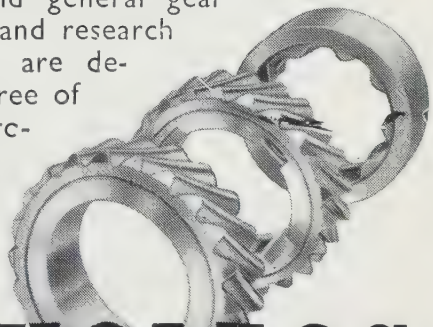
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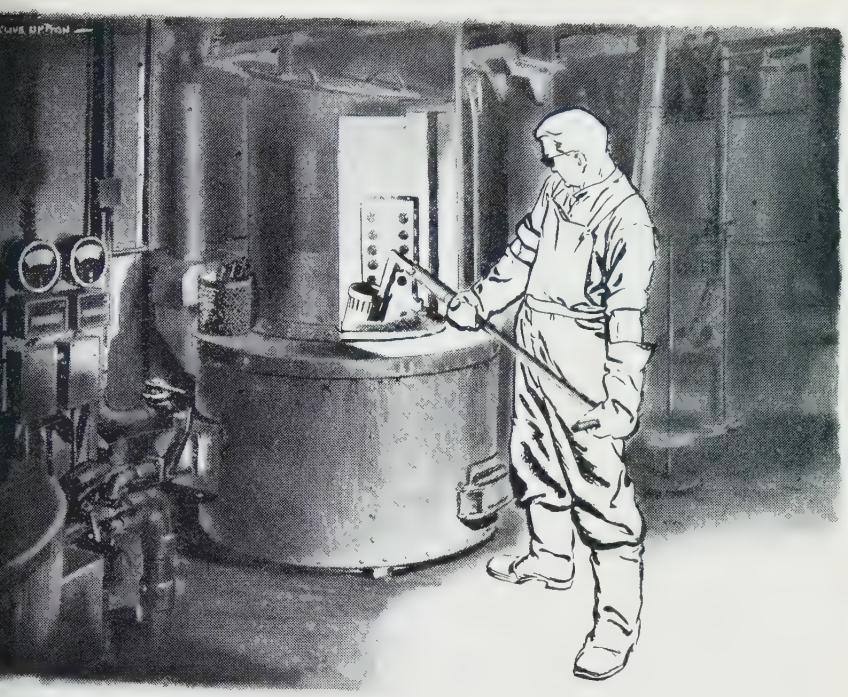
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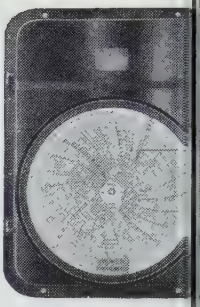
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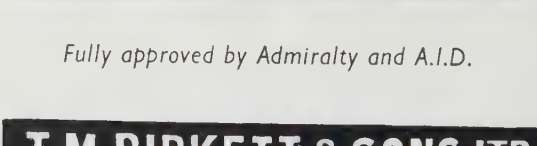
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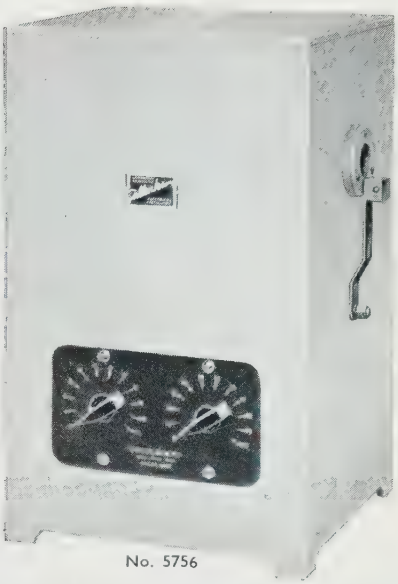

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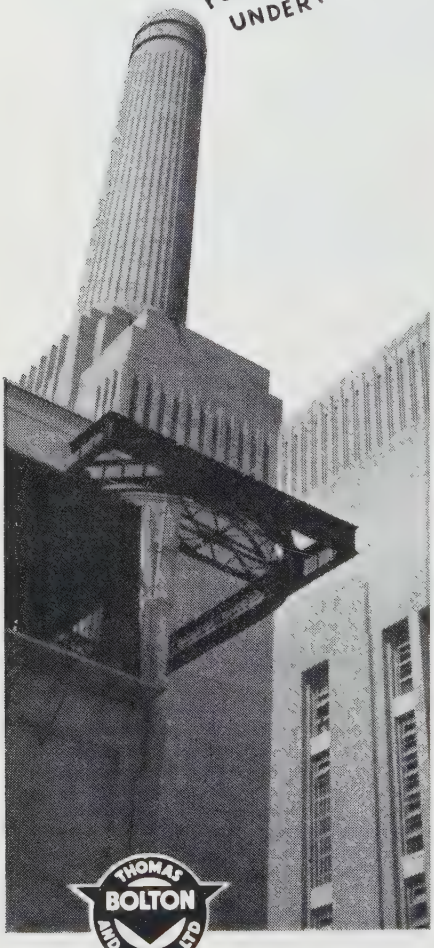
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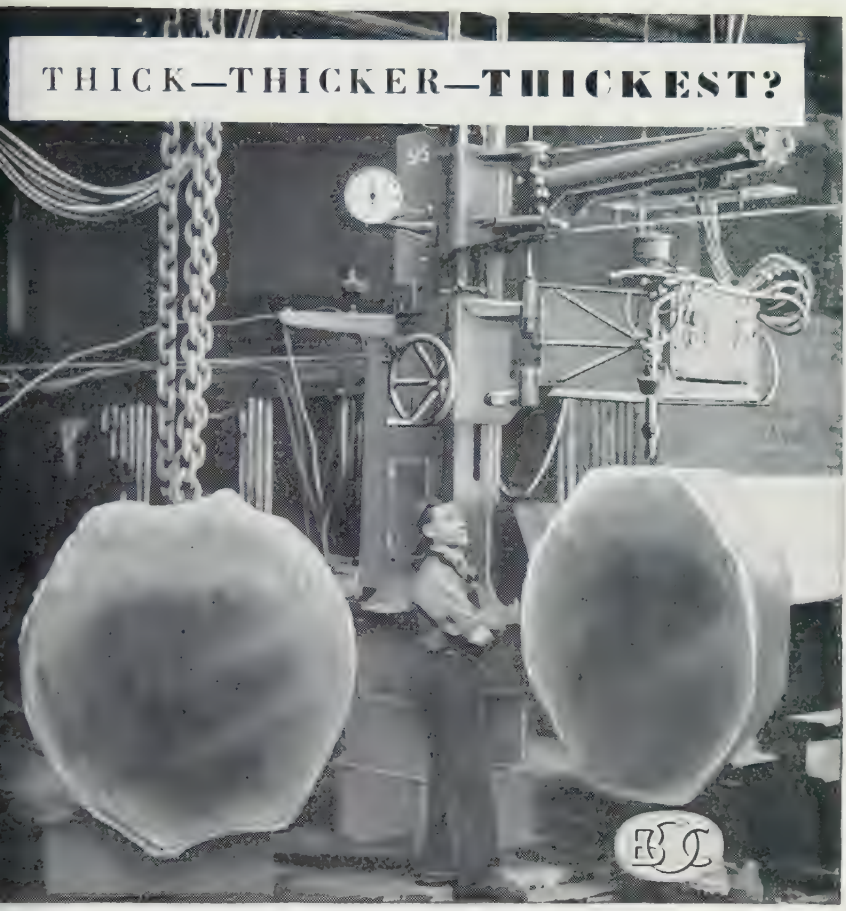

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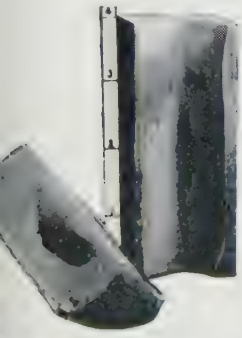
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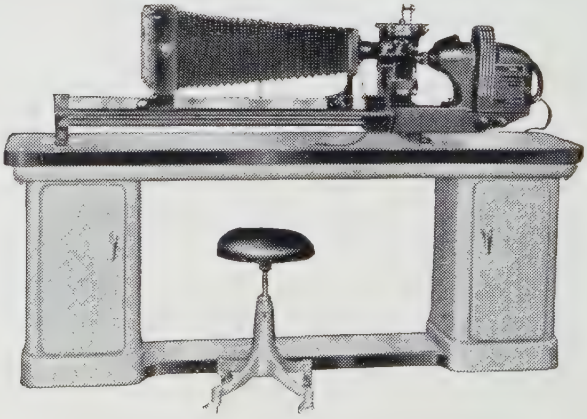
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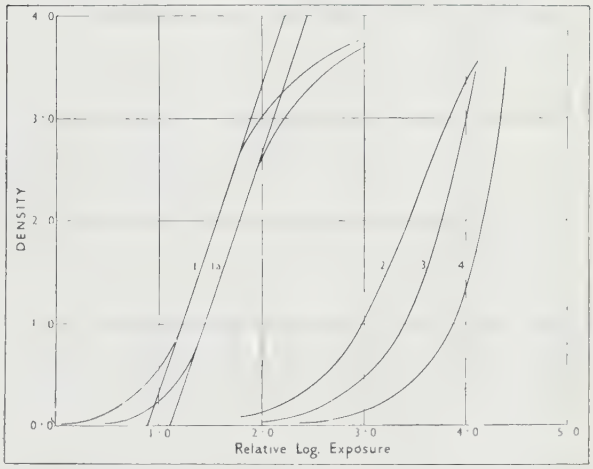
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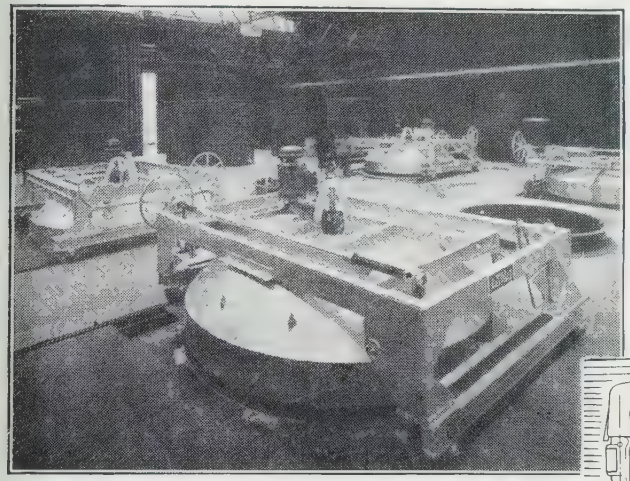
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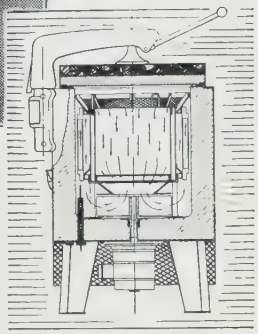
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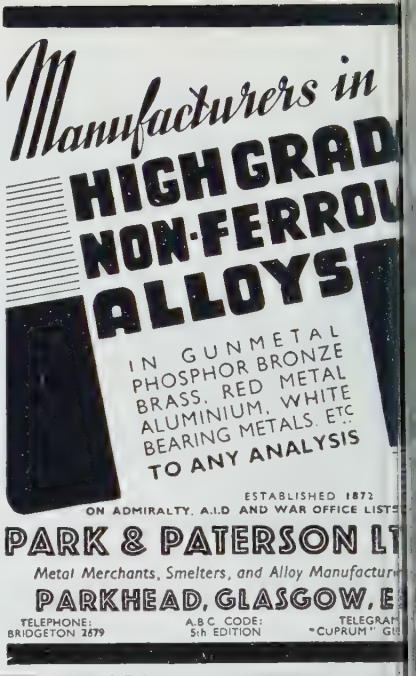


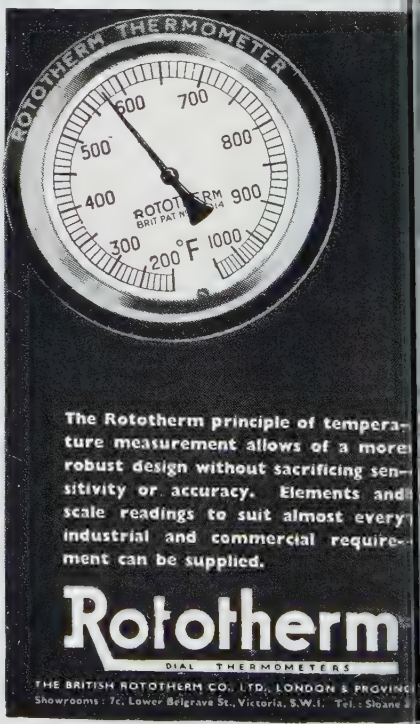
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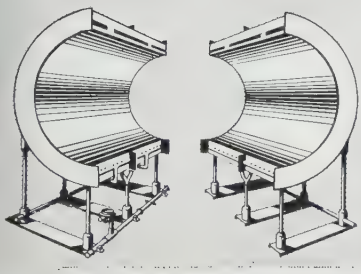
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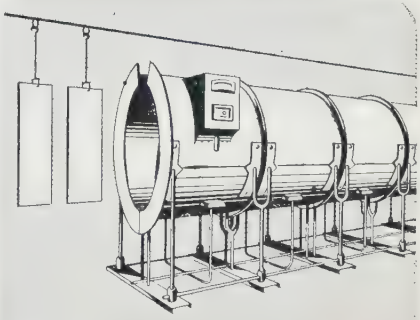

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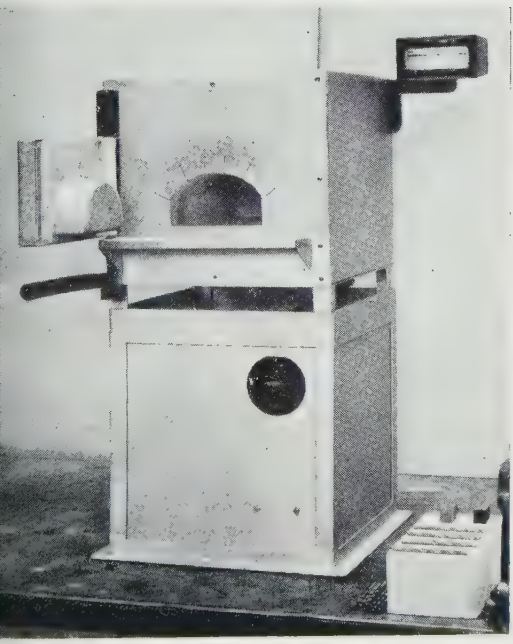
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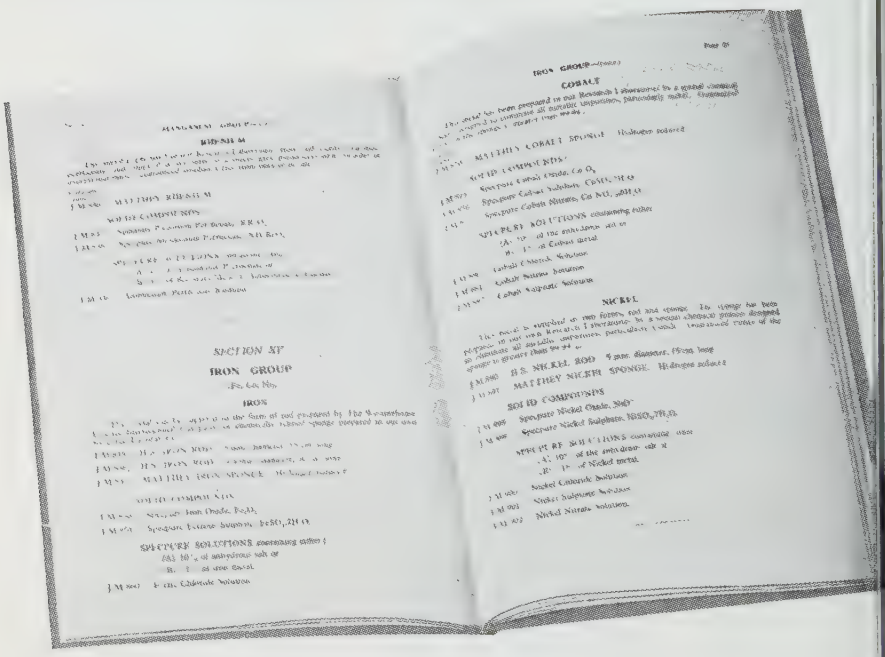
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OCTOBER 1947

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## INSTITUTE NEWS AND ANNOUNCEMENTS

### AUTUMN MEETING, GLASGOW

The Autumn Meeting, which took place in Glasgow from 23 to 26 September, was one of the most successful of its kind that has been held by the Institute. It was particularly remarkable for the very happy atmosphere which was created at the first social function and which was maintained throughout the meeting, for the care shown by the Reception Committee for members' comfort, the most generous hospitality offered to members and their ladies by the Scottish Local Section and others, and the interest of the works visited. The discussions of papers also maintained a high level.



Sir James Weir French, D.Sc., Honorary President of the Reception Committee.

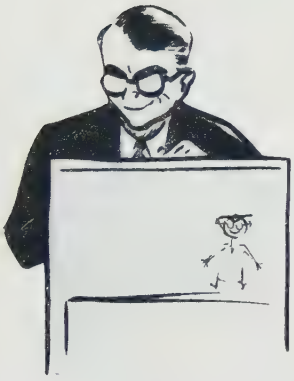
The Institute owes a great debt of gratitude to the Committee of the Scottish Local Section for organizing so memorable a meeting, and particularly to Mr. Matthew Hay, the Honorary Secretary to the Reception Committee, on whom fell the greater part of the large amount of administrative work in connection with it.

The meeting opened on the evening of Tuesday, 23 September, with Sir James Weir French, D.Sc., Honorary President of the Reception Committee, in the Chair, when members heard official addresses of welcome from the Chairman (on behalf of the Reception Committee), Councillor Andrew Hood, J.P. (representing the Lord Provost and Magistrates of the City of Glasgow), Professor R. Hay (representing the Principal of Glasgow University), and Mr. W. H. Marr, President of the Glasgow Chamber of Commerce. The President briefly replied.

Under the chairmanship of the President, Professor G. Wesley Austin, O.B.E., M.A., M.Sc., then delivered the Autumn Lecture on "The Metallurgical Resources of Scotland", which will be



GLASGOW MEETING. THE PRESIDENT, COLONEL P. G. J. GUETERBOCK, C.B., D.S.O., M.C., T.D., D.L., J.P., M.A., A.D.C. (*above*), AND THE HONORARY PRESIDENT OF THE RECEPTION COMMITTEE, SIR JAMES WEIR FRENCH, D.Sc



"The Professor"—Professor G. Wesley Austin, delivering the Autumn Lecture.

printed in an early issue of the *Journal*. Members and their ladies were then entertained to light refreshments and some Scottish songs [in the singing of the choruses of which they took part]. The welcome and this first social function struck the keynote of the very happy relations for which the meeting was so notable.

On the next day the morning was occupied by good discussions on papers by Mr. Ivor Jenkins on "Surface Effects During the Annealing of 70 : 30 Brass" and Dr. O. R. J. Lee and Dr. L. Northcott on "The Centrifugal Casting of Copper Alloy Wheels in Sand Moulds". At a luncheon that followed, the President thanked the Scottish Local Section for their invitation to hold the meeting in Glasgow, and Mr. A. Craig Macdonald, Vice-Chairman of the Section, replied. In the afternoon members visited the British Aluminium Company, Ltd., Falkirk; John Brown and Company, Ltd., Clydebank; Glenfield and Kennedy, Ltd., Kilmarnock; and Henry Wiggin and Company, Ltd., Thornliebank; while ladies visited the works of the Saxone Shoe Company, Ltd., Kilmarnock, or Burns' Cottage at Ayr.

In the evening members and their ladies were the guests of the Lord Provost (Sir Hector McNeill), Magistrates, and Corporation of Glasgow at a reception at the City Chambers. The Lord Provost, supported by the Magistrates, received the guests, and later made a brief address of welcome, to which the President replied. Sir James Weir French proposed a vote of thanks to the Institute's hosts. During the evening there was dancing (including Scottish dances) in the Banqueting Hall, and a concert.

On Thursday morning, very good discussions took place on a paper by Mr. P. G. Forrester on "Frictional Properties of Some Lubricated Bearing Metals", and a series of three papers on the corrosion of magnesium-rich alloys by Dr. F. A. Fox and Mr. J. K. Davies, Mr. C. J. Bushrod, and Mr. E. R. W. Jones and Mrs. M. K. Petch. Members were entertained by the Scottish Local Section to lunch, at which the Chairman, Mr. A. B. Graham, made a brief speech of welcome, to which the President replied. In the afternoon visits were paid to Albion Motors, Ltd., Scotstoun; Babcock and Wilcox, Ltd.,




Mr. A. B. Graham, Chairman of the Scottish Local Section.



Renfrew; and Barr and Stroud, Ltd., Anniesland. The ladies had been the guests of the Reception Committee on an all-day tour of the Trossachs.



Mrs. Craig Macdonald.

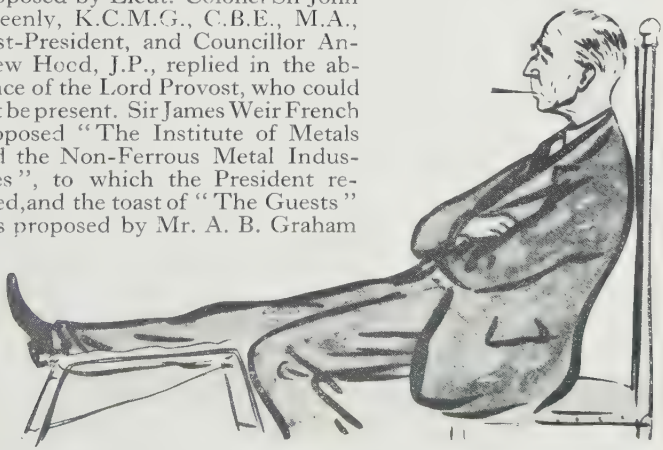


"Scotland Forever." —Mr. A. Craig Macdonald, Vice-Chairman of the Scottish Local Section.



Mr. Matthew Hay, Honorary Secretary of the Scottish Local Section.

In the evening a dinner and dance was held at the Grosvenor Restaurant. The guests were received by the Chairman (Sir James Weir French), Lady French, and the President and Mrs. Gueterbock, and included many who are distinguished in science and industry in the Glasgow area. The toast of "The City of Glasgow" was proposed by Lieut.-Colonel Sir John Greenly, K.C.M.G., C.B.E., M.A., Past-President, and Councillor Andrew Hood, J.P., replied in the absence of the Lord Provost, who could not be present. Sir James Weir French proposed "The Institute of Metals and the Non-Ferrous Metal Industries", to which the President replied, and the toast of "The Guests" was proposed by Mr. A. B. Graham



"The Boss."—The President, Colonel P. G. J. Gueterbock (who, because of an injury, was glad to use a leg-rest specially made for him, at a few hours' notice).

and was acknowledged by Mr. W. H. Marr, President of the Glasgow Chamber of Commerce. There was dancing, and during the evening Mrs. Gueterbock made a presentation to Mr. Matthew Hay, Honorary Secretary to the Reception Committee, on behalf of the Council of the Institute.

The last day of the meeting, Friday, 26 September, was occupied by an all-day steamer trip on Loch Lomond. It was a beautiful day and the Loch was seen at its best. In the course of the trip the Reception Committee presented all ladies with a sprig of white heather, and in the afternoon the ship was stopped while Mr. A. B. Graham and Mrs. Craig Macdonald, respectively, presented the President and Mrs. Gueterbock with mementos of the meeting. A piper played the party on and off the boat, during the trip, and for reels which were danced by some of the members and ladies present.

All who contributed to the success of this meeting, including the Ladies' Committee which so ably cared for the comfort of the lady visitors, fully deserved the warm thanks expressed so frequently to their hosts by all who were present. Members were surprised that, in these days of austerity, so much could be achieved in so many ways to make the meeting so successful. Scottish hospitality had, once again, excelled itself.

The caricatures were drawn at the Glasgow Meeting by Mr. James Greenlees.

### PHOTOGRAPHS TAKEN AT THE GLASGOW MEETING

A number of excellent photographs were taken at the Glasgow meeting, and it is desired to arrange for an album, which should be as complete as possible, that could be retained by the Scottish Local Section.

Will all members who took photographs on that occasion kindly send copies to the Secretary of the Institute for that purpose.

## PERSONALITIES

### Mr. H. H. A. Greer, J.P., Fellow.

Mr. H. H. A. Greer, J.P., who—as was announced in the August issue of the *Journal*—has been elected a Fellow in recognition of his outstanding services to the Institute for many years, was born in Belfast in 1875. He is well known in the metal trades of Scotland and has been connected with the metal industries for over 50 years.

For 20 years he was in business with his father, Mr. James C. Greer, and afterwards became the sole partner in the firm of James C. Greer and Son, Metal Merchants, of Glasgow, who have for many years been associated with Messrs. A. Cohen and Company, Ltd., of Great Dover Street, London. In 1918 Mr. Greer joined the Board of Directors of the latter Company, but retired some years ago.

An Original Member of the Institute, he took a large part in the formation of the Scottish Local Section in 1918. He was a member of the Committee of the Section from 1918 to 1944, Honorary Local Secretary from 1918 to 1928, and Chairman in 1931 and 1932. He was a Member of Council of the Institute from 1928 to 1936. Mr. Greer was a member of the Reception Committee of the Glasgow Meeting of the Institute in 1910, and



Honorary Secretary to the Reception Committee in connection with the Institute's very successful Autumn Meeting in Glasgow in 1925.

In the early days of the formation of the British Non-Ferrous Metals Research Association, he was its only member in Scotland, and acted as its Honorary Correspondent in Scotland. He is an Associate Member of the Institution of Engineers and Shipbuilders in Scotland, a Member of the Incorporation of Hammermen of Glasgow (founded in 1536), and a Member of the Incorporation of Gardeners, Glasgow (founded in 1605). He has held the position of Preses (Chairman) of the Weavers' Society of Anderston, Glasgow—a society founded in 1787, is a Justice of the Peace for the County of Ayr, and has been a member of the Parish Council of West Kilbride, Ayrshire.

Not only is Mr. Greer held in great esteem and affection in metallurgical and wider circles in Scotland, but his most attractive personality, his charm, and sense of humour have made him a very popular figure at the Institute's meetings—at home and abroad—which he very regularly attended until recent years.

## PERSONAL NOTES

Dr. N. P. Antia was taken ill and admitted to hospital while on a visit to the United States. He was, in consequence, unable to return to England as planned, before returning to India.

Mr. B. L. Averbach, M.Met.Eng., has been awarded the degree of Sc.D. in Metallurgy of the Massachusetts Institute of Technology and has accepted an appointment as Assistant Professor of Metallurgy at that Institute.

Mr. H. J. Axon, B.Met., has left the Inorganic Chemistry Laboratory, University Museum, Oxford, and is now at the Metallurgy Section, A.E.I. Laboratory, Aldermaston Court, Aldermaston, nr. Reading.

Mr. H. R. Bleakney's correspondence should be addressed c/o National Research Council, 356 Booth Street, Ottawa, Canada.

Sir Lawrence Bragg, F.R.S., O.B.E., M.C., has had the honorary degree of LL.D. conferred on him by the University of St. Andrews.

Ir. B. E. Cankrien has retired from the post of Librarian of the Technical Nautical and Aeronautical Institute, Rotterdam, Holland.

Mr. A. L. Carr, B.Sc., has left University College, Cardiff, to take up an appointment with the Research and Development Department of The Mond Nickel Company, Ltd., Wiggin Street, Birmingham.

Mr. K. C. Choudhouri, M.Sc., Chemist and Metallurgist to the E.I. Railway, is now at the Metallurgical Laboratory, Locomotive Works, E.I.R., P.O. Jamalpur, Dt. Monghyr, India.

Mr. C. R. Cox, B.C.S., is now President of the Carnegie Steel Corporation, Carnegie Building, Pittsburgh 30, Pa., U.S.A.

Dr. D. W. Davison, B.Sc., sailed for Australia on 24 September. His address is now Research School of Metallurgy, The University, Melbourne.

Mrs. U. S. C. Ende has left the British Welding Research Association to take up an appointment in the Chemistry Department of the British Iron and Steel Research Association.

Mr. G. B. Evans has been appointed Senior Metallurgist to Airspeed, Ltd., Somerford Road, Christchurch, Hants.

Mr. Harold M. Gade is now at the College of Engineering, Rutgers University, New Brunswick, N.J., U.S.A.

Colonel P. G. J. Gueterbock, C.B., D.S.O., M.C., T.D., D.L., J.P., M.A., A.D.C., President, has been elected an Honorary Member of the Chemical, Metallurgical, and Mining Society of South Africa for the year ending 30 June 1948.

Mr. M. K. Haldar, M.Sc., has left the Research Department of the London, Midland and Scottish Railway Company, Derby, and is taking a special course in industrial and engineering radiography, held under the auspices of Kodak, Ltd., Harrow.

Mr. John C. Hannam has taken up an appointment as Research Assistant in the Chemistry Department of the British Iron and Steel Research Association.

Mr. Russell G. Hardy, B.S., has left the University of Notre Dame, Notre Dame, Ind., and is now Process Engineer at the Howard Foundry, 1700 N. Kostner St., Chicago, Ill., U.S.A.

Mr. John D. Haworth has been awarded the degree of B.Met. (First-Class Honours) and has also received the Mappin and Nesthill Medals at Sheffield University. He is now at the Inorganic Chemistry Laboratory, University Museum, Oxford.

Mr. J. L. Heselgrave, B.Met., has left his appointment at the Surbiton County Grammar School to take up a post as Mathematics Master at Tadcaster Grammar School, Tadcaster, Yorks.

Instructor-Lieutenant G. W. Horsley, R.N., has changed his address to: H.M.S. *President*, R.N. College, Greenwich, London, S.E. 10. He was recently awarded the B.A. degree of Cambridge University.

Mr. H. F. Johnson is now on foreign service. He should be addressed 8483 H. F. Johnson, S.Q. 8/1/4 Palm Grove, c/o A.I.O.C., Abadan, South Iran.

Mr. Henry J. Kozlowski, B.Sc., is on one year's leave of absence from the Bureau of Mines, Ottawa, Canada, to undertake post-graduate studies in the Department of Metallurgy of the University of Birmingham.

Mr. P. J. Liptrot, M.Eng., has left Avonmouth to take up an appointment as Works Metallurgist to the National Smelting Company, Ltd., Swansea Vale Works, Llansamlet, Swansea, Glam.

Mr. Herbert Meier, Dipl.Ing., has left The George Fischer Steel and Iron Works, Ltd., Schaffhausen, and is now with George Fischer, Ltd., Schaffhausen, Switzerland.

Dr. L. Northcott has been appointed Superintendent of Research, Armament Research Department, Ministry of Supply, Woolwich.

Mr. James Patrick, A.R.T.C., has left Scotland and is now at The British Aluminium Company, Ltd., Salisbury House, London Wall, London, E.C.2.

Mr. R. Pearce, B.A., has left Oxford to take up a position in the Research Laboratories of the British Aluminium Company, Ltd., Chalfont Park, Gerrards Cross, Bucks.

Dr. R. V. Riley, B.Sc., has now taken up the post of Research Manager at the Staveley/Bradley and Foster Research Department, and correspondence should be addressed to him at the Staveley Coal and Iron Company, Staveley, near Chesterfield.

Mr. J. Sandor, D.I.C., has left the British Coal Utilization Research Association to take up an appointment as Research Metallurgist with Carbometals, Ltd., London.

Mr. P. W. Smith has recently joined the staff of the O. and F. Company, Hobart, Tasmania.

Professor E. C. R. Spooner, D.Sc., B.E., D.Phil., has left England, and his address is now University of Adelaide, North Terrace, Adelaide, South Australia.

Mr. Robert C. Stanley has been awarded His Majesty's Medal for Services in the Cause of Freedom, in recognition of his valuable services to the Allies.

Mr. Stanley is Chairman and President of the International Nickel Company of Canada, Ltd., and, in over 40 years of service, has played a major part in the development of this important Canadian industry. He has been President of this Company since 1922 and, in addition, Chairman since 1937.

Besides his valuable work in the industrial sphere, Mr. Stanley was an active member of the British War Relief Society in America during the war, for which he collected over a quarter of a million dollars.

Mr. Stanley, who has been on his first post-war visit to England, left for New York on 26 September. On behalf of the Institute, a telegram of congratulation was addressed to him on the award of the honour bestowed on him by The King.

Mr. L. J. Stone returned to Australia on 2 October 1947. His address now is Rollings Road, Upper Ferntree Gully, Victoria, Australia.

Mr. V. Subramaniam, B.Sc., B.Met., has left Calcutta and is now at the Department of Metallurgical Engineering, 1218 John Jay Hall, Columbia University, New York 27, N.Y., U.S.A.

Mr. D. J. Leighton Thomas is now on the R.E.O. Staff, H.Q. Land North Rhine and Westphalia, Düsseldorf, Germany.

Mr. G. L. Turner has been awarded the degree of B.Sc. in Metallurgy of Birmingham University, has been elected a Graduate of the Institution of Mechanical Engineers, and has left the University to take up an appointment as Metallurgist at The Bridge Foundry Company, Ltd., Wednesbury. In October 1938 Mr. Turner commenced reading metallurgy at Birmingham University; he joined the Fleet Air Arm in January 1940 and was commissioned as a Lieutenant (A), R.N.V.R., in December 1940. In July 1941 he was taken prisoner and remained a prisoner-of-war until May 1945. He was released from the service in November 1945 and had resumed his studies at Birmingham during the previous month.

Mr. J. Walker, B.Sc., A.R.S.M., has been appointed to the Board of Directors of the Morgan Crucible Company, Ltd., London.

Mr. S. Walsh, A.M.T.C., is now employed in the Research Department of Taylor Bros. and Company, Ltd., Trafford Park Steel Works, Trafford Park, Manchester 17.

Mr. B. R. Warren has arrived in England from the Middle East Force, R.A.F. His address is Alma House, Great Hockham, Norwich.

Mr. N. G. Wright, B.Sc., has left the Manganese Bronze and Brass Company, Ltd., Birkenhead, to take up an appointment with Roan Antelope Copper Mines, Ltd., P.O. Luanshya, Northern Rhodesia.

## DEATHS

The Editor regrets to record the deaths of:

Flying Officer P. J. Danielsen, who was reported missing on 28 May 1940, now presumed killed in action.

Mr. T. A. E. Holdengarde, O.B.E., on 4 August 1947.

*Note:* Will members (in addition to informing the Institute's administrative department of changes of address, occupation, &c.) kindly notify the Editor, separately, of all changes of occupation, appointments, movements, awards of honours and degrees, &c., as these are matters which interest their fellow members? Such notes should reach the Editor not later than the 23rd day of each month.

# LOCAL SECTIONS NEWS

## ASSOCIATED METALLURGICAL SOCIETIES

Members are reminded that, by special arrangement, members of the Institute of Metals may attend and receive notices of all meetings of the Leeds Metallurgical Society and of the Manchester Metallurgical Society, the Presidents and Honorary Secretaries of

which attend meetings of the Institute's Local Sections Committee by invitation.

It is necessary for members to notify the Secretary of the Institute of their desire to be granted these facilities; the Institute then makes a payment to the two societies in respect of all such registrations.

### Leeds Metallurgical Society

The officers and programme of the Society for the session 1947–48 are given below:

*President:*
A. Preece.

*Past-President:*
Major G. H. Kitson.

*Vice-Presidents:*
W. R. Berry.
J. Arthur Sykes.

*Honorary Treasurer:*
D. E. Catton.

*Committee:*
R. E. Campbell.
K. J. Irvine.
F. Lindars.
H. F. Poole.
H. D. Ward.
J. Wilkinson.

*Honorary Secretary:*
W. J. G. Cosgrave, 24 Wellhouse Road, Leeds, 8.

*Programme of Meetings.*

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| 1947. | |
| Thurs., 2 Oct. | Mr. Edwin Davis: "Industrial Copper Alloys." |
| Thurs., 6 Nov. | Mr. R. G. Wilkinson: "Magnesium Alloys." |
| Wed., 3 Dec. | Mr. H. G. Warrington: "Aluminium Alloys." |
| 1948. | |
| Thurs., 8 Jan. | Symposium on "Casting". |
| Thurs., 5 Feb. | Mr. C. P. Miller: "Investigation of Failures." |
| Thurs., 4 Mar. | Joint Meeting with members of the Iron and Steel Institute. Discussion of an Iron and Steel Institute paper. |
| Sat., 13 Mar. | Social evening. |
| Thurs., 1 Apr. | Mr. Ivor Jenkins, M.Sc.: "Controlled Atmospheres." |
| Thurs., 6 May. | Annual General Meeting and papers by Student Members. |

The meetings are held in the Main Lecture Theatre, The Chemistry Department, The University, Leeds, at 7 p.m.

## Manchester Metallurgical Society

The officers and programme of the Society for the session 1947–48 are given below:

*President :*

L. C. Bannister, Ph.D.

*Ex-President :*

R. S. Brown, M.B.E.

*Vice-Presidents :*

D. Binnie, Ph.D.
A. H. Goodger, M.Sc.

*Hon. Secretary :*

J. A. Tod, B.Sc., I.C.I., Ltd., Metals Division, Broughton Copper Works, Manchester.

*Hon. Treasurer :*

Norman Youatt.

*Council :*

H. Allison, B.Sc.Tech.
A. B. Ashton, M.Sc.
W. Cartwright, M.Sc.
E. J. Heeley, Assoc.Met.
N. S. Hubbard, B.Sc.
D. Menzies.
M. L. Meyer.
R. C. Stockton.
A. B. Winterbottom, M.Sc.
W. B. Wragg, B.Sc.Tech.

*Programme of Meetings.*

1947.

Wed., 15 Oct. Dr. L. C. Bannister, B.Sc. Presidential Address : " Conduction of Electricity."

Wed., 5 Nov. Mr. E. Jones, M.Sc. : " Electrical Strain Gauges."

Wed., 26 Nov. Mr. E. W. Colbeck, M.A. : " Some Metallurgical Problems in the Field of Atomic Energy." (Joint Meeting with the Iron and Steel Institute and the Institute of Metals.)

Wed., 10 Dec. Mr. Ivor Jenkins, M.Sc. : " Controlled Atmospheres for Heat-Treatment of Metals."

1948.

Wed., 28 Jan. Mr. E. Davis, M.Sc. : " Some Metallurgical Aspects of Jointing Non-Ferrous Materials."

Wed., 11 Feb. Mr. T. F. Russell, Assoc.Met. : " Isothermal Heat-Treatment of Alloy Steels."

Wed., 3 Mar. Mr. E. Mills : " Metallurgical Problems Arising from the Use of Non-Ferrous Metals in the Telecommunication Industry."

Wed., 17 Mar. "Modern Heat-Treatment Furnaces." Discussion opened by Mr. R. S. Brown, M.B.E. Annual General Meeting.

The meetings are held in the Engineers' Club, Albert Square, Manchester, at 6.30 p.m.

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# UNIVERSITY NEWS

## DEPARTMENT OF METALLURGY, UNIVERSITY OF BIRMINGHAM

Dr. G. V. Raynor has been appointed Reader in Theoretical Metallurgy, and Mr. D. W. Wakeman, who is working on problems related to the thermo-chemistry of alloys, under the direction of Dr. Raynor, has been awarded the William Gibbins Fellowship.

The degree of D.Sc. was conferred upon F. A. Fox, J. H. Partridge, and W. T. Pell-Walpole at the last degree congregation. Dr. Pell-Walpole has been awarded an I.C.I. Research Fellowship in Metallurgy and is continuing to work in the Department on the melting and casting of tin bronzes.

## UNIVERSITY OF MELBOURNE

A Rosenhain Club of Melbourne has been inaugurated at the University School of Metallurgy, consisting of physical metallurgists, engineers, physicists, and others interested in the physical properties of metals. The aims of the group are to perpetuate the memory of Dr. Walter Rosenhain, who was a graduate of the University, and also to form a meeting ground for a group of scientists who have common interests. The club meets monthly in Professor Greenwood's room at the University.

It is hoped to sponsor the Rosenhain Memorial medal annually.

Mrs. M. Kirsner (*née* Nancy Rosenhain) is a patron of the club, and Dr. J. L. Haughton and Dr. Marie L. V. Gayler are Honorary Members.

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# OTHER NEWS

## METALLURGICAL REFRESHER COURSE

From 5 to 7 September 1947 the Institution of Metallurgists held its first Refresher Course for metallurgists, and it is hoped that such gatherings will become a regular feature of metallurgical practice.

In the beautifully appointed L.M.S. School of Transport in Derby some 70 members of the Institution, representing all grades of membership, lived and worked together over the week-end. The theme of the studies was "The Transformations in Solid Metals and Alloys", and the following lectures were given and informal discussion took place:

Lecture 1.—A general review of the subject, by Professor F. C. Thompson, M.Sc., D.Met. (Manchester University).

Lecture 2.—The Transformation of Austenite in Steels, by Professor J. H. Andrew, D.Sc. (Sheffield University).

Lecture 3.—The Determination of Time–Temperature–Transformation Curves in Steels, by E. H. Bucknall, M.Sc. (The Mond Nickel Company, Ltd.).

Lecture 4.—The Practical Aspects of Austempering, Martempering, and other Treatment for Steels, by J. Shaw, B.Sc., A.R.C.S. (Wm. Jessop and Sons, Ltd.).

Lecture 5.—The Formation of Graphite in Cast Iron and Related Alloys, by J. G. Pearce, M.Sc. (British Cast Iron Research Association).

Lecture 6.—Atomic Changes in Solid Solutions including Age-Hardening, by G. V. Raynor, M.A., D.Phil. (Birmingham University).

Lecture 7.—Order–Disorder Transformations in Solid Solutions, by G. V. Raynor, M.A., D.Phil. (Birmingham University).

While the newer physical methods of approach to problems of transformation received a good deal of attention, it was apparent that there is still room for further development and greater use of the more classical methods of the older school of metallurgists in the study of this subject.

All present were convinced that this type of meeting is likely in the future to play a most important part in the work of the Institution.

## THE INSTITUTION OF HEATING AND VENTILATING ENGINEERS JUBILEE CELEBRATIONS

In view of the present national conditions, the Council of the Institution regretfully decided to cancel the arrangements to hold a Jubilee Banquet and Dance on Tuesday, 7 October. It was agreed, therefore, to confine the celebrations to technical meetings, and the final arrangements were :

Tuesday, 7 October, 5.30 for 6 p.m. Special Jubilee meeting in the Lecture Theatre, The Institution of Civil Engineers, Great George Street, London, S.W.1, when Mr. C. G. Carrothers, B.Eng., read a paper on "Practical Relations Between Heat and Electric Forms of Energy with Special Reference to District Heating".

Wednesday, 8 October, 5.30 for 6 p.m. Autumn Special Meeting in the Lecture Theatre, The Institution of Mechanical Engineers, Storey's Gate, London, S.W.1, when Mr. C. G. Vokes read a paper "Air Filtration in War as Applied to Peace Conditions".

## THE PHYSICAL SOCIETY

Miss A. C. Stickland, Ph.D., has been appointed to the post of Secretary-Editor, and assumed her duties on 1 September 1947.

## BRITISH WELDING RESEARCH ASSOCIATION

Dr. H. G. Taylor, D.I.C., has been appointed Director of Research in succession to Dr. A. Ramsay Moon.

## MECHANICAL ENGINEERING RESEARCH

Under the directorship of Dr. G. A. Hankins, the Government is setting up an organization to carry out research in mechanical engineering. It has been decided to do this through the Department of Scientific and Industrial Research, and the plan of the new organization will be based on the recommendations of a D.S.I.R. Committee on Mechanical Engineering Research.

Its purpose will be to meet and anticipate the needs of industry and government departments, and it is intended to supplement the research carried out in other organizations. The subjects which are to be investigated are :

(*a*) Properties and strength of materials.
(*b*) Mechanics of solids, stress, stability, and vibration of structures.
(*c*) Mechanics of fluids ; aerodynamics, gas dynamics, and hydraulics in their mechanical and engineering applications.
(*d*) Lubrication, wear, and mechanical engineering aspects of corrosion.
(*e*) Mechanisms, engineering metrology, and noise control.
(*f*) Mechanics of formation of materials ; machine shaping of materials.
(*g*) Heat transfer, heat exchange apparatus, and applied thermodynamics.

The location of the research station has not yet been decided, but for the time being the work will be carried out at the National Physical Laboratory and in the mechanical engineering laboratories of the Universities.

## MACHINE TOOL & ENGINEERING EXHIBITION, LONDON, 1948

The 1948 Exhibition will open at Olympia on 26 August 1948, and close on 11 September 1948. It will be the largest show of machine tools, woodworking machine equipment, and accessories ever staged in Great Britain. The three halls at Olympia have been taken and the exhibition will occupy nearly a quarter of a million square feet of space.

The Exhibition will be international in scope. Foreign exhibits will be shown side by side with British equipment, and users will be able to compare the respective merits and observe the developments that have taken place.

## WOMEN'S LEGION SCHOLARSHIP IN AERONAUTICAL ENGINEERING

The Women's Legion and the Women's Engineering Society announce the foundation of a new Scholarship for women, which will be awarded every two years. The winner will be enabled to train in any branch of aeronautical engineering. Girls who have passed the School Certificate examination and are aged between 15 and 20 will be eligible, and applications for the first Scholarship must be received before 30 April 1948.

## THE INDUSTRIAL FUTURE OF GREAT BRITAIN

A course of fifteen weekly lectures on the above subject is to be delivered, under the auspices of the University of London (Centre for Courses on International Affairs) and the Institute of Bankers, at the Beaver Hall of the Hudson's Bay Company, Garlick St., London, E.C.4 (near Mansion House Station). The course will be held on Tuesdays, at 6–7.30 p.m., commencing on 4 November 1947. The fee for the course is one guinea, and admission is by ticket only. As seating in the Hall is limited, tickets must be applied for in advance ; none will be issued at the door.

Members of the Institute of Metals are invited to register for this course.

The lectures, each of which will be followed by a discussion, are : 4 *Nov.*, Professor T. S. Ashton, M.A. : " The Industrial Past " ; 11 *Nov.*, Professor G. C. Allen, Ph.D., M.Com. : " Impact of the War " ; 18 *Nov.*, Anthony Hurd, M.P. : " Agriculture " ; 25 *Nov.*, Robert Stone, M.A. : " Iron and Steel " ; 2 *Dec.*, Sir Jonah Walker-Smith : " Building " ; 9 *Dec.* (speaker not announced) : " Fuel and Power " ; 16 *Dec.*, M. R. Bonavia : " Inland Transport " ; 13 *Jan.*, F. W. Paish, M.C., M.A. : " Finance of Reconstruction " ; 20 *Jan.*, Leslie Gamage, M.C., M.A. : " The Export Drive " ; 27 *Jan.* (speaker not announced) : " Shipping " ; 3 *Feb.*, H. Haygarth Jackson, M.C. : " Textiles and Export " ; 10 *Feb.*, S. R. Dennison, C.B.E., M.A. : " New Industrial Development and Export " ; 17 *Feb.*, Albert Palache : " Long-Term Finance of Enterprise " ; 24 *Feb.*, Professor Sir Arnold Plant, B.Com., B.Sc. : " Industrial Controls in War and Peace " ; 2 *Mar.* (speaker not announced) : " Industrial Change."

## IRON AND STEEL INSTITUTE

### Autumn Meeting, London

The Autumn Meeting of the Institute will he held at 4 Grosvenor Gardens, London, S.W.1, on Wednesday, 12 November (10 a.m.–1 p.m. ; 2.30–5 p.m.) and Thursday, 13 November 1947 (10 a.m.–12.45 p.m.). On the first day of the meeting a buffet luncheon (price 6*s.*) will be served in the library.

Papers to be presented and discussed will be :

*Wed.*, 12 *November*

(1) Jointly (10.15–11.45 a.m.) : J. H. Andrew, H. Lee, K. H. Lloyd, and N. Stephenson, " Hydrogen and Transformation Characteristics in Steel " ; and C. Sykes, H. H. Burton, and C. C. Gegg, " Hydrogen in Steel Manufacture ".

(2) Jointly (11.45 a.m.–1 p.m.) : W. Barr and C. F. Tipper, " Brittle Fracture in Mild Steel Plates " ; W. Barr and A. J. K. Honeyman, " The Effect of the Manganese–Carbon Ratio on the Brittle Fracture of Mild Steel " ; and W. Barr and A. J. K. Honeyman, " Some Factors Affecting the Notched-Bar Impact Properties of Mild Steel ".

(3) Jointly (2.30–4.15 p.m.) : J. E. de Graaf, " A Note on Variations in Producer Gas Quality " ; M. L. Hughes, " The Distribution of Fuel in Gas Producers " ; and M. L. Hughes, " Experiments on Gas Flow in Producer Fuel Beds ".

(4) T. Land, " A Photoelectric Roof Pyrometer for Open-Hearth Furnaces " (4.15–5 p.m.).

*Thurs., 13 November*

(1) R. Jackson, D. Knowles, T. H. Middleham, and R. J. Sarjant, " The Fluidity of Steel " (10.0–10.45 a.m.).

(2) A. H. Jay, " The Mechanism of Carbon Removal by Oxidation from the Open-Hearth Furnace " (10.45–11.45 a.m.).

(3) W. L. Kerlie, " Some Aspects of the Refining of High-Phosphorus Iron " (11.45 a.m.–12.45 p.m.).

### IRON AND STEEL ENGINEERS' GROUP

A meeting of the Group will be held at 4 Grosvenor Gardens, London, S.W.1, on Wednesday, 26 November 1947. A buffet lunch (price 6*s.*) will be served in the library.

Papers to be presented and discussed will be :

*Morning* (10.30 *a.m.*–12.45 *p.m.*)

" The Mechanical and Electrical Features of Primary Hot-Rolling Mill Auxiliaries." Section I.—" Mechanical Features ", by W. W. Franklin ; Section II.—" Electrical Features ", by P. F. Grove.

*Afternoon* (2.0–4.30 *p.m.*)

" Modern Small Rolling Mills ", by G. A. Phipps.

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## LOCAL SECTIONS MEETINGS

Birmingham Local Section.—Dr. G. V. Raynor, M.A. : " The Determination of Constitution Diagrams." (James Watt Memorial Institute, Great Charles Street, Birmingham, Thursday, 6 November 1947, at 6.30 p.m.)

Birmingham Local Section.—Mr. W. E. Ballard : Film on " Metal Spraying " and talk on " Protective Coatings." (James Watt Memorial Institute, Great Charles Street, Birmingham, Thursday, 27 November 1947, at 6.30 p.m.)

London Local Section.—Professor C. W. Dannatt, A.R.S.M., D.I.C. : " Some Aspects of Metal Refining." (Royal School of Mines, South Kensington, London, S.W.7, Thursday, 13 November 1947, at 7 p.m.)

Scottish Local Section.—Mr. A. Craig Macdonald, B.Sc. : " Commentary on a Visit to America." (Institution of Engineers and Shipbuilders in Scotland, 39 Elmbank Crescent, Glasgow, C.2, Monday, 10 November 1947, at 6.30 p.m.)

Sheffield Local Section.—Mr. A. J. Murphy, M.Sc. : " Magnesium Alloys." (Mining Lecture Theatre, Department of Applied Science, The University, St. George's Square, Sheffield, Friday, 21 November 1947, at 7.30 p.m.)

Swansea Local Section.—Sir Arthur Smout, J.P. : " The Place of the Metallurgist in Industry." (Guildhall, Swansea, Wednesday, 19 November 1947, at 6.30 p.m.)

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## OTHER MEETINGS

Diesel Engine Users' Association.—G. B. Fox : " Factors Affecting Piston Temperature." (Caxton Hall, Caxton Street, London, S.W.1, Thursday, 27 November 1947, at 2.30 p.m.)

Geological Society of London.—Ordinary Evening Meeting. (Burlington House, Piccadilly, London, W.1, Wednesday, 12 November 1947, at 5 p.m.)

Institute of Welding.—Presidential Address, by Mr. J. L. Adam, C.B.E. (Institution of Civil Engineers, Great George St., London, S.W.1, Wednesday, 29 October 1947, at 6 p.m.)

Institute of Welding, South London Branch.—R. R. Sillifant, "Argon Arc Welding." (Wandsworth Technical Institute, London, Thursday, 6 November 1947, at 6.30 p.m.)

Institute of Welding, West of Scotland Branch.—S. M. Reisser: "Welding of Structures." (Institution of Engineers and Shipbuilders in Scotland, 39 Elmbank Crescent, Glasgow, Thursday, 27 November 1947, at 6.45 p.m.)

Institute of Works Managers.—Mr. C. T. Melling: "Meeting the Industrial Power Crisis." (Waldorf Hotel, London, W.C.2, Wednesday, 29 October 1947, at 6.30 p.m.)

Institute of Works Managers.—Mr. G. Chelioti: "Some American Impressions." (Waldorf Hotel, London, W.C.2, Wednesday, 26 November 1947, at 6.30 p.m.)

Institute of Works Managers, Glasgow Branch.—Mr. C. A. Oakley: "An Industrial Survey of Scotland." (Institution of Engineers and Shipbuilders in Scotland, 39 Elmbank Crescent, Glasgow, C.2, Monday, 27 October 1947, at 7 p.m.)

Institute of Works Managers, Glasgow Branch.—Mr. M. McLachlan: "Industrial Relations: Employers, Employees, and the State." (Institution of Engineers and Shipbuilders in Scotland, 39 Elmbank Crescent, Glasgow, C.2, Monday, 24 November 1947, at 7 p.m.)

Institute of Works Managers, Liverpool Branch.—Miss A. G. Shaw: "Motion Study." (Exchange Hotel, Liverpool, Tuesday, 11 November 1947, at 6.45 p.m.)

Institute of Works Managers, Manchester Branch.—Mr. G. M. Davies: "Oil Firing." (Engineers' Club, Albert Square, Manchester, Friday, 14 November 1947, at 6.30 p.m.)

Institution of Engineers and Shipbuilders in Scotland.—J. A. Kilby and W. G. Cameron: "Steel Processing." (The Institution, 39 Elmbank Crescent, Glasgow, Tuesday, 4 November 1947, at 6.30 p.m.)

Institution of Mechanical Engineers.—Discussion on the Manufacture of Turbine Blades for the Whittle Engine, by Mr. T. A. Kestell. (The Institution, Storey's Gate, London, S.W.1, Friday, 31 October 1947, at 5.30 p.m.)

Institution of Mining and Metallurgy.—G. W. M. Eaton Turner: "Some Notes on the Bibiani Gold Mine, West Africa"; H. A. McGowan: "Treatment at the Bibiani (1927), Ltd., Gold Mine, West Africa." (Geological Society, Burlington House, Piccadilly, London, W.1, Thursday, 20 November 1947, at 5 p.m.)

Iron and Steel Institute.—Autumn Meeting; for details see p. xlvi. (4 Grosvenor Gardens, London, S.W.1, Wednesday and Thursday, 12 and 13 November 1947.)

**Iron and Steel Institute, Iron and Steel Engineers' Group.**—Reading and discussion of two papers; for details see p. xlvii. (4 Grosvenor Gardens, London, S.W.1.)

**Leeds Metallurgical Society.**—Mr. R. G. Wilkinson: "Magnesium Alloys." (Main Lecture Theatre, Chemistry Department, The University, Leeds, Thursday, 6 November 1947, at 7 p.m.)

**Manchester Metallurgical Society.**—E. Jones, M.Sc.: "Electrical Strain Gauges." (Engineers' Club, Albert Square, Manchester, Wednesday, 5 November 1947, at 6.30 p.m.)

**Manchester Metallurgical Society.**—E. W. Colbeck, M.A.: "Some Metallurgical Problems in the Field of Atomic Energy." Joint Meeting with the Iron and Steel Institute and the Institute of Metals. (Engineers' Club, Albert Square, Manchester, Wednesday, 26 November 1947, at 6.30 p.m.)

**North-East Coast Institution of Engineers and Shipbuilders.**—Dr. T. W. F. Brown: "A Marine Turbine Research and Testing Station." Andrew Laing Lecture. (The Institution, Bolbec Hall, Newcastle-upon-Tyne, Friday, 31 October 1947.)

**Royal Aeronautical Society.**—Sir William T. Griffiths, D.Sc.: "The Problem of High Temperature Alloys for Gas Turbines." (Institution of Civil Engineers, Great George Street, London, S.W.1, Thursday, 23 October 1947, at 6 p.m.)

**Sheffield Metallurgical Association.**—R. B. Heywood: "Photoelasticity Applied to Design Problems." (198 West Street, Sheffield 1, Tuesday, 28 October 1947, at 7 p.m.)

**Sheffield Metallurgical Association.**—Dr. C. Sykes, F.R.S., H. H. Burton, and C. C. Gegg: "Hydrogen in Steel Manufacture"; Professor J. H. Andrew, Dr. H. Lee, H. K. Lloyd, and N. Stephenson: "Hydrogen and Transformation Characteristics in Steel." Joint Meeting with the Iron and Steel Institute. (198 West Street, Sheffield 1, Tuesday, 4 November 1947, at 7 p.m.)

**Sheffield Metallurgical Association.**—J. C. Williamson: "The Metallurgy of Musical Instruments." (198 West Street, Sheffield 1, Tuesday, 11 November 1947, at 7 p.m.)

**Sheffield Metallurgical Association.**—Professor Leslie Aitchison, D.Met., B.Sc. (title to be announced later). (198 West Street, Sheffield 1, Tuesday, 25 November 1947, at 7 p.m.)

**Sheffield Society of Engineers and Metallurgists.**—Sir Alwyn Crow, C.B.E.: "The Rocket as a Weapon of War." Thomas Hawksley Lecture. Joint meeting with the Yorkshire Branch of the Institution of Mechanical Engineers. (Royal Victoria Station Hotel, Sheffield, Monday, 24 November 1947, at 6.15 p.m.)

**Swansea and District Metallurgical Society.**—Mr. M. R. Hopkins, M.Sc.: "Metal Surfaces." (Royal Institution of South Wales, Swansea, Saturday, 15 November 1947, at 6.30 p.m. Members of the Institute of Metals are invited.)

**West of Scotland Iron and Steel Institute.**—Dr. C. Sykes, F.R.S.: "The Selection and Use of Steel for Steam Turbines." (Institution of Engineers and Shipbuilders in Scotland, 39 Elmbank Crescent, Glasgow, Friday, 21 November 1947, at 6.45 p.m.)

## APPOINTMENT REQUIRED

GRADUATE METALLURGIST (Member of the Institute of Metals), now in Polish Resettlement Corps, with good experience in metal testing and heat-treatment, and as University lecturer, seeks appointment research work or industrial testing of non-ferrous metals or steel. Box No. 215, Institute of Metals, 4 Grosvenor Gardens, London, S.W.1.

## APPOINTMENTS VACANT

*To conform to the requirements of the Control of Engagement Order, 1947, these advertisements are published for the information of those who are classified as "excepted persons" under the Order, only.*

ANALYTICAL CHEMISTS required who should preferably be qualified and have experience in the assaying of non-ferrous metals, minerals, and by-products, including the rarer metals. Liberal salary will be paid. Apply to Derby and Co., Ltd., Cheyne House, 62–63 Cheapside, London, E.C. 2.

SENIOR METALLURGIST, aged 30–45, with degree or equivalent qualification and industrial experience, required by long-established heavy non-ferrous foundry in the North-West. Living accommodation available. Box No. 213, Institute of Metals, 4 Grosvenor Gardens, London, S.W.1.

THE MOND NICKEL COMPANY invites applications for the following posts in its Research Laboratory, Wiggin Street, Birmingham :

1. SENIOR WELDING INVESTIGATOR (30 to 38) with experience in metallurgical research, preferably in connection with the welding of alloy steels. Salary not less than £700 p.a.
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Salary figures refer to the lower limit of age and experience. All the above posts are of a permanent nature, offering opportunities for advancement. Candidates appointed will be eligible for membership of the Company's non-contributory pensions scheme. Apply to : The Manager, Development and Research Department, The Mond Nickel Company, Limited, Grosvenor House, Park Lane, London, W.1. Envelopes should be marked "R.L. Confidential".

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG, SOUTH AFRICA. Applications are invited for a SENIOR LECTURER IN METALLURGY. Salary scale £800 × 40–£1000 per annum, plus a temporary cost of living allowance which at present amounts to £75 per annum for married men, or persons with dependents, and £46 16s. per annum for others. Membership of the University Teachers' Provident Fund Scheme is compulsory, and involves a contribution of 6% (which may shortly be raised to 7%) from the member's salary; the University and the Government together contributing an equal amount.

The duties of the post are concerned principally with Ferrous and Physical Metallurgy, and previous experience in these branches is therefore essential. Some industrial experience will be considered an advantage. Duties are to be assumed on 1 January 1948, or as soon as possible thereafter. Further particulars may be obtained from The Secretary, Universities Bureau of the British Empire, 8 Park Street, London, W.1. Closing date for receipt of applications is 17 November 1947.

## ERRATUM

*Journal, August* 1947, p. xxxvii.

The entry regarding Mr. W. West is incorrect as regards his association with Leyland Motors, Ltd.; he still retains his seat on the Board of Directors. The remainder of the information given is accurate. The error is regretted.

No.....

**Form A.** *(Membership Application)* Recd.....

# The INSTITUTE of METALS

*4 Grosvenor Gardens, London, S.W.1.*
*Founded* 1908. *Incorporated* 1910.

*To the Secretary,*
*The Institute of Metals.*

I, the UNDERSIGNED.....

being.....years of age and desirous of becoming a*.....
Member of the **Institute of Metals,** agree that if elected will be governed by the Regulations and Bye-laws of the Institute from time to time extant and observe the obligations imposed on Members under the Articles of Association of the Institute, and that I will advance the interests of the Institute so far as may be in my power ; and we, the undersigned, from our personal knowledge, do hereby recommend the said.....for election.

Name of applicant in full.....

Address .....

Business or Profession†.....

.....

.....

Qualification .....

Degrees and/or honorific distinctions.....

Dated this.....day of....., 19.....

.....
.....
.....
} Signatures of three Members.

---

The Council, having approved the above recommendation, declare the applicant to be duly elected as.....
Member of the **Institute of Metals.**

.....
*Chairman.*

} To be filled up by the Council.

*Dated this.....day of.....19.....*

* **For Qualifications of Members, see other side.** An applicant for Student Membership must state date of birth.

† Name and address of firm (or other body) should be stated as well as position held.
*(It would be a convenience if the Candidate's Card were sent with this form.)*

## OBJECTS OF THE INSTITUTE

The main objects for which the Institute was formed in 1908 are :

(*a*) To promote the science and practice of non-ferrous metallurgy in all its branches.

(*b*) To afford a means of communication between members of the non-ferrous metal trades upon matters bearing upon their respective manufactures, other than questions connected with wages, management of works, and trade regulations.

(*c*) To facilitate the exchange of ideas between members, and between members and the community at large, by holding meetings and by the publication of literature.

(*d*) To establish branches either in the United Kingdom or abroad.

A free copy of the Articles of Association may be obtained by prospective Members on application to the Institute.

## MEMBERSHIP

**Ordinary Members** must be not less than 21 years of age, and either :

(*a*) persons engaged in the manufacture, working or use of non-ferrous metals and alloys, or

(*b*) persons of scientific, technical, or literary attainments connected with or interested in the metal trades or with the application of non-ferrous metals and alloys, or engaged in their scientific investigation.

**Student Members** are admitted and retained as such within the ages of 17 and 28 years of age. They receive the same privileges as members, except that they are not entitled to vote at meetings or to nominate candidates for ordinary or associate membership. They must be either :

(*a*) Students of metallurgy.

(*b*) Pupils or assistants of persons qualified for Ordinary Membership, whether such persons are actually members of the Institute or not.

## SUBSCRIPTIONS

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## JOINT MEMBERSHIP WITH THE IRON AND STEEL INSTITUTE

Applicants for membership of the Institute of Metals may, when submitting their applications, also complete a form (obtainable from the Secretary, Institute of Metals) applying for joint membership with the Iron and Steel Institute.

The subscriptions and entrance fees of such Joint Members are :

**Joint Ordinary Membership :** Subscription, £6 6s. ; entrance fee, £2 2s.

**Joint Student Membership Institute of Metals/Associateship Iron and Steel Institute :** Subscription, £2 12s. ; no entrance fee.

# CALCULATION OF LOADS INVOLVED IN METAL STRIP ROLLING.* 1111

By MAURICE COOK,† D.Sc., Ph.D., Member of Council, and EUSTACE C. LARKE.‡

Synopsis.

Various formulæ have been advanced for calculating the loads involved in the cold rolling of strip and sheet materials, but because of the several assumptions they contain, they are only of limited application and only very approximate. Moreover, in applying the formulæ, arbitrarily chosen values have to be adopted for the coefficient associated with the friction conditions in the roll throat, and it is necessary to determine experimentally the resistance to deformation as a function of the amount of reduction in thickness effected. Furthermore, none of the methods so far proposed makes any allowance for the effect of roll-face distortion.

Attention has, therefore, been directed to developing a method of computing rolling loads which dispenses with the need for the individual determination of the influence of these several factors, including roll-face distortion. The derivation of the method is based on the assumption that the magnitude of the pure work of rolling is independent of the number of passes used in effecting a given reduction in thickness, and the basic experimental data required consist only of a few measured values of the rolling loads developed in rolling one material under a series of different sets of rolling conditions. From these data, rolling loads can then be readily computed for practices involving any number of passes, or a sequence of reductions in thickness can be established for which a constant load is developed in each pass.

Results calculated by this method can be directly checked against measured values, and comparisons which have been made between calculated values and those obtained experimentally on steel and copper, in the course of investigations carried out by the British Iron and Steel Research Association, show good agreement over the range of reductions encountered in normal rolling-mill procedure.

## I.—Introduction.

In recent years several attempts have been made to derive a general formula for calculating the loads involved in flat rolling, i.e. strip or sheet rolling, and with the exception of that due to Ekelund,[1] these have been based on purely theoretical considerations of the mechanics of rolling. Von Kármán,[2] Trinks,[3] and Tselikov[4] have each advanced expressions from which it is possible to compute rolling loads, but because of the several assumptions which had to be made and the various mathematical simplifications which were introduced in the

* Manuscript received 17 June 1947.

† Director, Imperial Chemical Industries, Ltd., Metals Division, Witton, Birmingham.

‡ Research Department, Imperial Chemical Industries, Ltd., Metals Division, Witton, Birmingham.

underlying mathematical treatment of the rolling process, these formulæ are only of limited application and very approximate.

The most comprehensive and exact analysis of the dynamics of rolling has been carried out by Orowan,[5] who did not assume that resistance to deformation was constant, but took into consideration work-hardening which takes place during cold rolling. In using this method of calculation, however, it is necessary to determine experimentally curves of resistance to deformation, and this may necessitate consideration of the effect of inhomogeneous deformation. It is also necessary to assume or establish an average value for the frictional forces developed in the roll throat, but it is open to question if such an average figure would be adequate, and, as in other formulæ, no allowance is made for the distortion of the roll face over the arc of contact.

In view of the doubts and difficulties associated with the determination of acceptably accurate values assignable to the influence of roll flattening, friction, and resistance to deformation, the authors have given their attention to the development of a method of rolling-load computation which avoids the necessity of determining values of the various factors individually, by any theoretical or practical procedures. The method is based on, and makes use of, a minimum of data in the form of initial rolling-load measurements. It is very simple to apply, and the accuracy of the results can be readily and directly checked with measured values of rolling loads.

## II.—Derivation of Method of Calculation.

The method described for calculating rolling loads is based on the assumption that the magnitude of the pure work of rolling is independent of the number of passes used in effecting a given reduction in thickness. From Fig. 1, it will be appreciated that the pure work of rolling during one revolution of both rolls can be stated as :

$$W = 4\pi\beta eP$$

The meaning of these and other symbols used throughout the paper is indicated in Fig. 1.

The increase in kinetic energy of the material, associated with the difference in exit speed of the strip and the peripheral speed of the rolls, is negligible, and the values of these speeds have, therefore, been taken as identical. Hence, the number of revolutions of the rolls during the first pass can be written as :

$$N_1 = L_1/2\pi r$$

the total amount of pure work during the first pass being :

$$W_1 = 2P_1\beta_1 e_1 L_1/r.$$

Putting

$$e_1 = \sqrt{r(t_0 - t_1)} \text{ and } L_1 = t_0 L_0 / t_1,$$

the pure work, $W_1$, becomes:

$$W_1 = 2P_1 t_0 L_0 \beta_1 \sqrt{r(t_0 - t_1)}/rt_1 \quad . \ . \ . \quad \text{1st pass}$$

Similarly:

$$W_2 = 2P_2 t_0 L_0 \beta_2 \sqrt{r(t_1 - t_2)}/rt_2 \quad . \ . \ . \quad \text{2nd pass}$$

and

$$W_n = 2P_n t_0 L_0 \beta_n \sqrt{r(t_{n-1} - t_n)}/rt_n \ . \ . \ . \quad n\text{th pass}$$

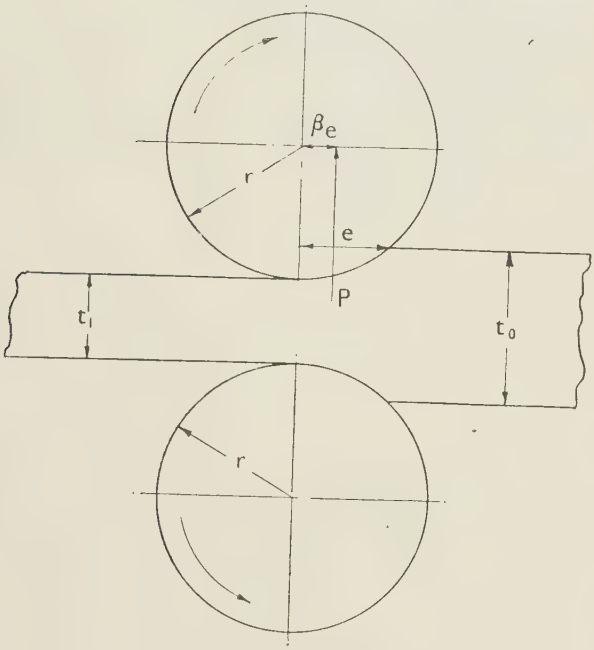



Fig. 1.

Key.

$W$ = Pure work of rolling.
$\beta$ = Projected length of arc of contact.
$L_1$ = Length of strip after 1st pass.
$t_1$ = Thickness after 1st pass.
$P$ = Rolling load.
$L_0$ = Length of strip before 1st pass.
$t_0$ = Thickness before 1st pass.
$r$ = Roll radius.

The suffix (1) indicates conditions after the 1st pass.
" (2) " " " 2nd pass.
" (3) " " " 3rd pass.
" ($n$) " " " $n$th pass.
" ($s$) " " when a total reduction obtained in a number of light passes is achieved in one heavy pass.

If instead of $n$ light passes, the total reduction made during these passes is effected in one heavy pass, then, using the suffix $S$ to denote the condition of one heavy pass :

$$W_S = 2P_S t_0 L_0 \beta_S \sqrt{r(t_0 - t_n)}/rt_n.$$

The length $\beta e$ in Fig. 1 is termed the lever arm and is defined as the horizontal distance between the vertical centre line of the rolls and the line of action of the resultant of the total rolling load. The moment of this force opposes the rotational motion of the rolls, so that if the pure torque which is needed to counteract the moment of the rolling load is divided by the product of the load and the length $e$, the value of $\beta$ can be found. Consideration of experimental results, which are discussed later, justifies the decision to treat $\beta$ as a constant.

Since it is assumed that the pure energy required to effect a given total reduction in one heavy pass is the same as the sum of the individual energies developed at each of a number of lighter passes, it follows that :

$$W_1 + W_2 + \ldots + W_n = W_S.$$

Hence :

$$P_1\sqrt{(t_0 - t_1)}/t_1 + P_2\sqrt{(t_1 - t_2)}/t_2 + \ldots + P_n\sqrt{t_{n-1} - t_n}/t_n = P_S\sqrt{(t_0 - t_n)}/t_n \quad . \quad . \quad (1)$$

the factor $2t_0 L_0 \beta \sqrt{r}/r$ being cancelled from both sides of the equation.

Since : $100\,(t_0 - t_1)/t_0 = R_1$

$100\,(t_0 - t_2)/t_0 = R_2$

and $100\,(t_0 - t_n)/t_0 = R_n$

equation (1) can be rewritten as :

$$P_1\sqrt{R_1}/(100 - R_1) + P_2\sqrt{(R_2 - R_1)}/(100 - R_2) + \ldots + P_n\sqrt{(R_n - R_{n-1})}/(100 - R_n) = P_S\sqrt{R_n}/(100 - R_n) \quad . \quad . \quad (2)$$

With this equation and an experimentally derived curve—later referred to as a first-pass basic curve—relating $P_S$ to reductions effected in one pass on any one mill, the loads $P_1$, $P_2$, $P_3$, &c., developed when the same total reduction is effected in a number of smaller passes, can be determined. Conversely, if, for a series of individual passes, the loads $P_1$, $P_2$, $P_3$, &c., are known, then the load $P_S$, corresponding to one heavy pass, can also be computed.

The only means of checking the validity and accuracy of any method of calculation is, of course, by reference to actually determined load values where this is possible, as it is with this method. In all the other methods so far described, such a direct comparison cannot be made because it is not possible to assign accurate values to

the coefficient of friction, variation in resistance to deformation by rolling, and roll-face distortion.

### III.—Experimental Measurements of Rolling Loads.

All the determined load values which have been used for checking the method, and which are referred to more fully later, have been obtained by Dr. Hugh Ford [6] and his collaborators in the course of a very comprehensive investigation carried out at the Sheffield station of the British Iron and Steel Research Association. Some of the results of this work dealing with the cold rolling of a 0·11%-carbon silicon-killed steel, and a 0·07%-carbon rimming steel, have already been published, while those results relating to the other materials, a 0·2–0·25%-carbon steel and H.C. copper of three different initial thicknesses, have yet to be published. The authors are very grateful to the British Iron and Steel Research Association and to Dr. Ford for their kindness and courtesy in allowing them access to this information and for permission to make use of some of these results in the present paper. The curves in Figs. 2–4, the values recorded in Tables II–IV, and the measured loads plotted in Figs. 5–11 have all been obtained from this source.

All the cold rolling was carried out on the experimental two-high mill with 10-in.-dia. rolls under very accurately controlled conditions which have been described elsewhere.[7] In cold rolling the hot-broken-down 0·11%-carbon silicon-killed steel, 2·3 in. wide, at an initial thickness of 0·074 in., individual strips were reduced in thickness by 5, 10, 15, 20, 30, and 40% in one pass. Afterwards, the strips already reduced in thickness during the first pass by 5%, were subjected to a further 10 passes, each of 5% relative to the thickness before each pass. The material reduced in one pass by 10% was also given a further 13 passes, each of 10%, again relative to the thickness before each pass. Similarly, the 15, 20, 30, and 40% samples were further reduced in 8, 7, 3, and 2 passes respectively, the percentage reduction at each pass for each series being the same as for the first pass, but always with reference to the thickness before the pass. Each test was carried out at least in duplicate. During the whole of the rolling of this and other material referred to later, adequate lubrication was ensured by a liberal supply of Vacuum 40A rolling oil to the surface of the strip.

A set of corresponding data was also determined using an annealed 0·07%-carbon rimming steel, 3·3 in. wide, at an initial thickness of 0·064 in. For each of the various reductions obtained, the rolling load and roll torque were measured.

Similar comprehensive series of tests were also carried out on

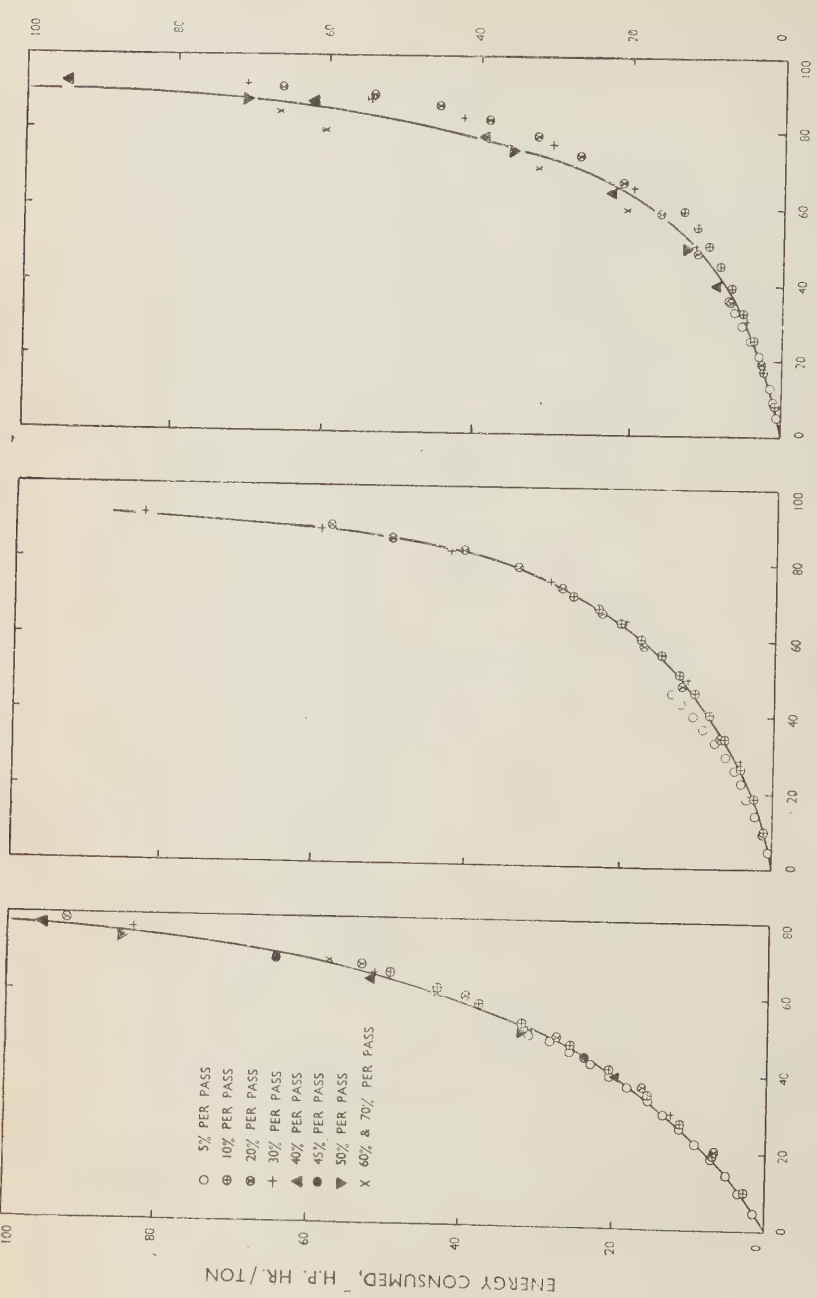



FIG. 2. FIG. 3. FIG. 4.

Total Pure Energy Values as Determined by Ford.

annealed 0·2–0·25%-carbon electric-furnace steel 3 in. wide and 0·1 in. thick, and annealed H.C. copper 3 in. wide in three initial thicknesses, i.e. 0·1, 0·075, and 0·05 in. As before, the rolling load and energy consumption were recorded for each pass.

The measured energy consumption, in horse-power hours per ton, required to effect the reduction of the material only, i.e. the pure work of rolling, has been plotted against the total percentage reduction for one of the steels and one of the coppers, the results being shown in Figs. 2 and 3. From Ford's values, given in Table I, in which the reduction per pass is relative to the thickness before each pass, it will be seen that the total energy is the sum of the useful energy consumed at each pass; and these few results serve to show how the curves have been constructed.

The total-energy values in Table I are included in Fig. 2, where they all lie on a smooth curve. All the other values plotted in Fig. 2 but not included in Table I also lie on the curve, and the comparable results for the other two steels in turn follow similarly smooth curves.

TABLE I.

| Pass No. | Reduction, %. | | Useful Energy, h.p. hr./ton. | |
|---|---|---|---|---|
| | Per Pass. | Total. | Per Pass (measured). | Total. |
| 1 | 20·3 | 20·3 | 6·86 | 6·86 |
| 2 | 20·6 | 36·7 | 9·46 | 16·32 |
| 3 | 20·3 | 49·5 | 11·35 | 27·67 |
| 4 | 20·7 | 60·0 | 11·95 | 39·62 |
| 5 | 19·8 | 67·9 | 13·45 | 53·07 |

The surface condition of the rolls used for this part of the research was described as a mirror finish, grinding having been carried out with a 400-grit wheel. This standard of finish was also operative during the rolling of the 0·1-in.-thick copper, and measured energy values for this material are plotted in Fig. 3. These plotted points also can be connected by a smooth curve.

After this phase of the investigation, the rolls were reground with a 180-grit wheel, the resultant surface finish being described as dull matte. Copper was then rolled at respective initial thicknesses of 0·1, 0·075, and 0·05 in. The energy values determined when rolling the 0·1-in. copper with this roll surface are plotted in Fig. 4, from which it will be seen that for this series of results there is a certain amount of scatter of the points relative to the smoothly drawn curve.

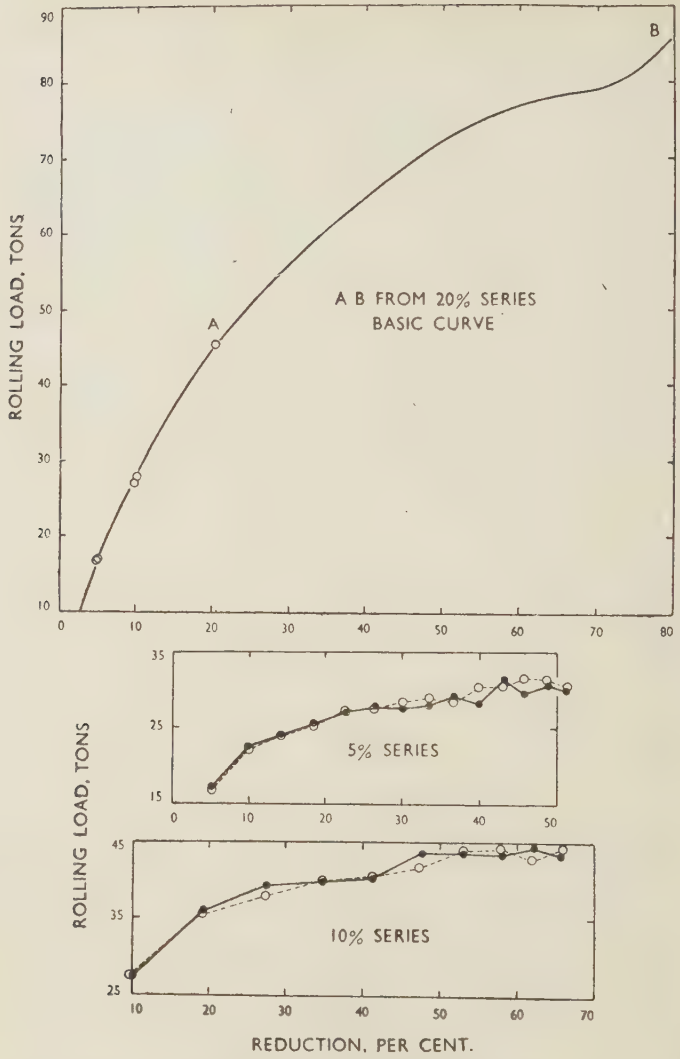



Fig. 5.—Annealed 0·2/0·25%-carbon Electric Furnace Steel, 3·0 in. Wide, 0·1 in. Initial Thickness. Roll surface : ground mirror finish (wheel grit 400).

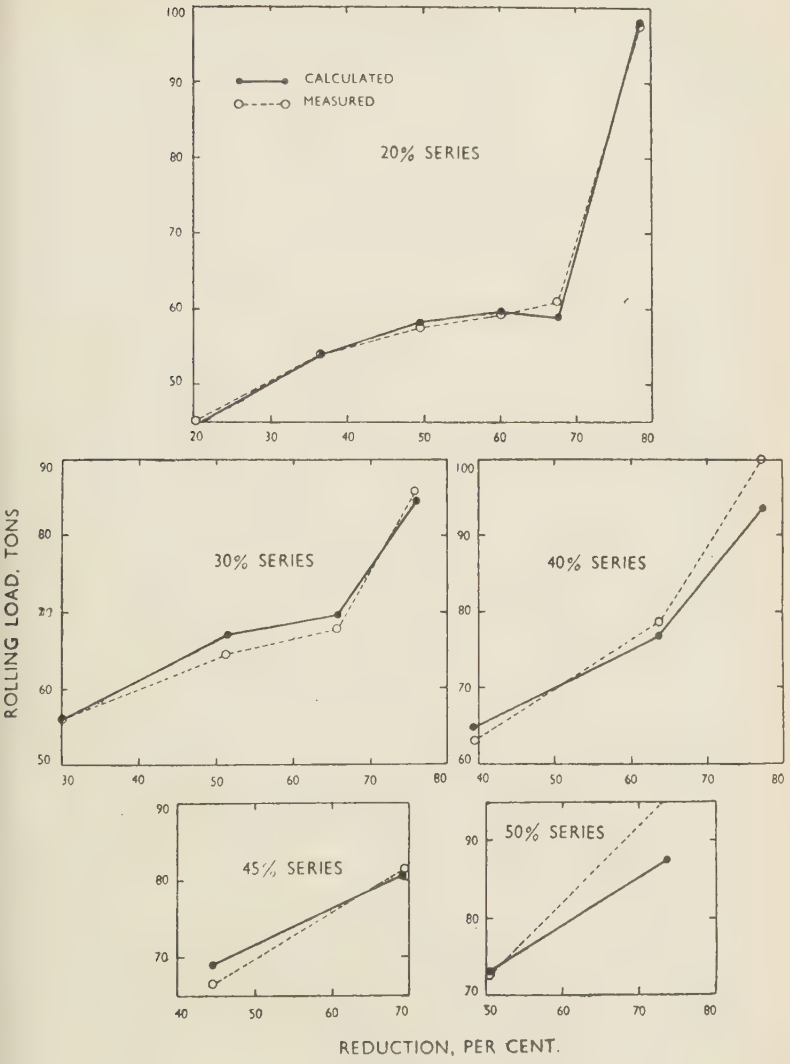



FIG. 5 (*continued*).

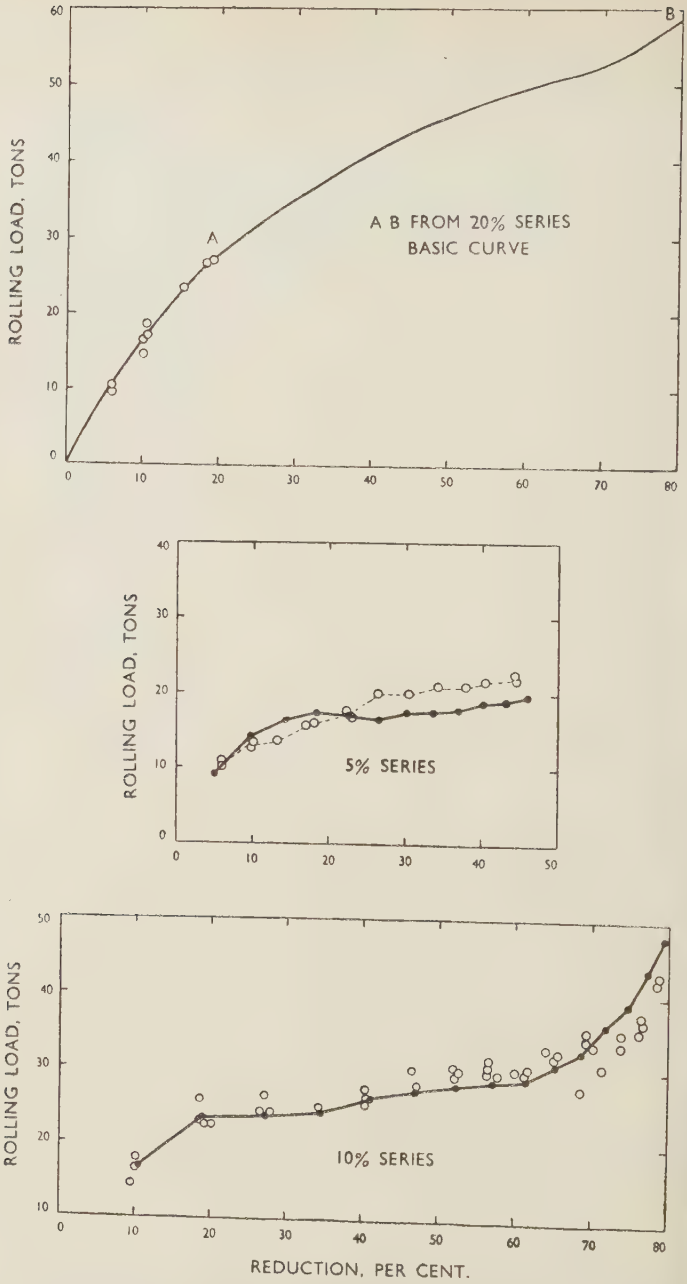



Fig. 6.—Annealed 0·11%-carbon Killed Steel, 2·3 in. Wide, 0·074 in. Initial Thickness. Roll surface: ground mirror finish (wheel grit 400).

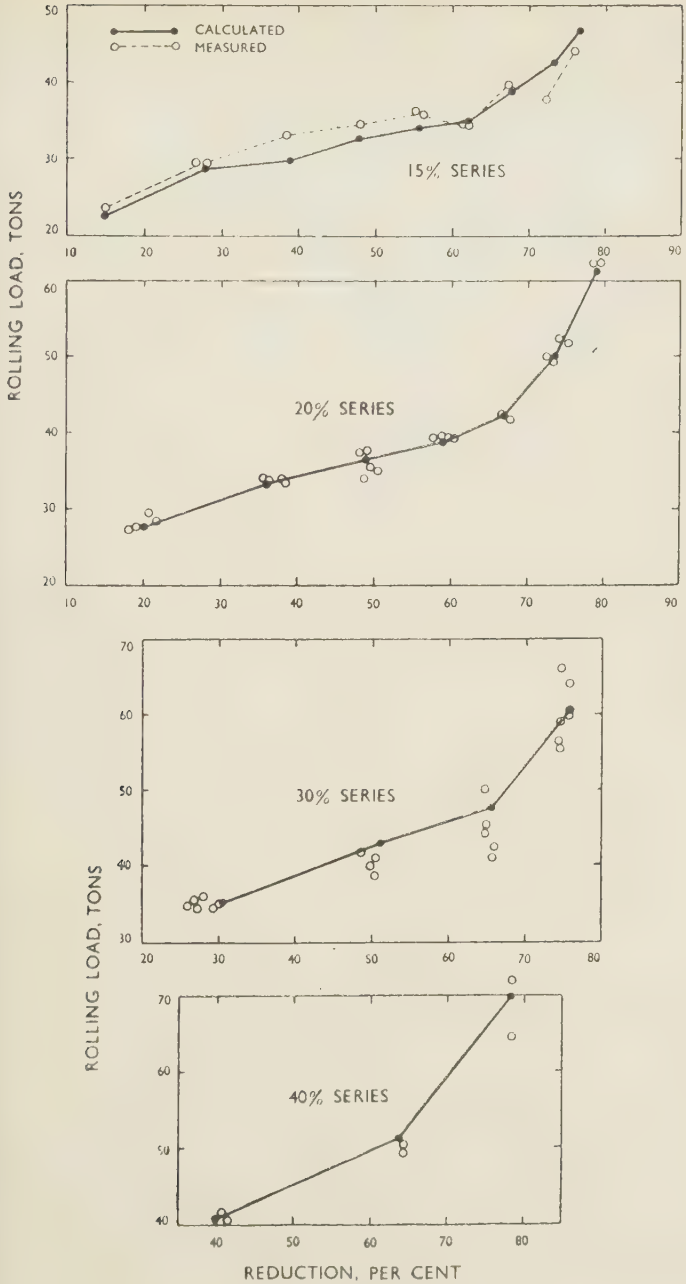



FIG. 6 (*continued*).

A similar scattering of the results was associated with the data for the 0·075 and 0·05-in.-thick copper.

The experimental data plotted in Figs. 2, 3, and 4 clearly show

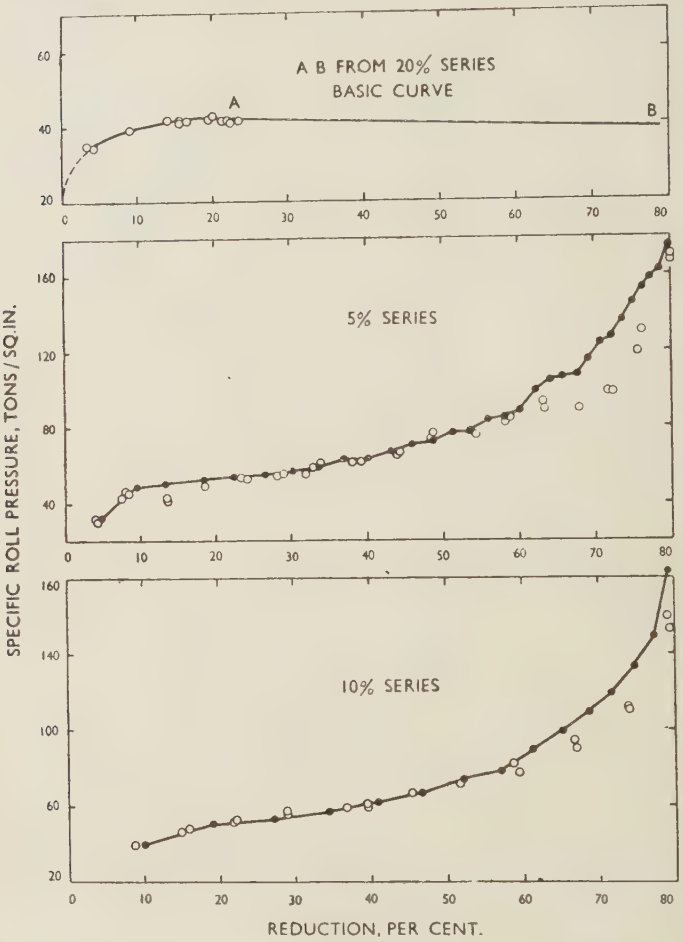



Fig. 7.—Hot-Rolled 0·07%-carbon Rimming Steel, 3$\frac{5}{16}$ in. Wide, 0·063 in. Initial Thickness. Roll surface: ground mirror finish (wheel grit 400).

that, for the rolling conditions considered, the same amount of pure work of rolling is expended whether a given reduction in thickness is effected in one heavy pass or in a number of lighter passes. The only other assumption made in this method of calculation is that the ratio

of the lever arm ($\beta e$ in Fig. 1) to the horizontally projected length of the arc of contact ($e$) would be constant when rolling any one thickness of material under constant conditions. The justification or otherwise of this assumption can readily be established by experiment since,

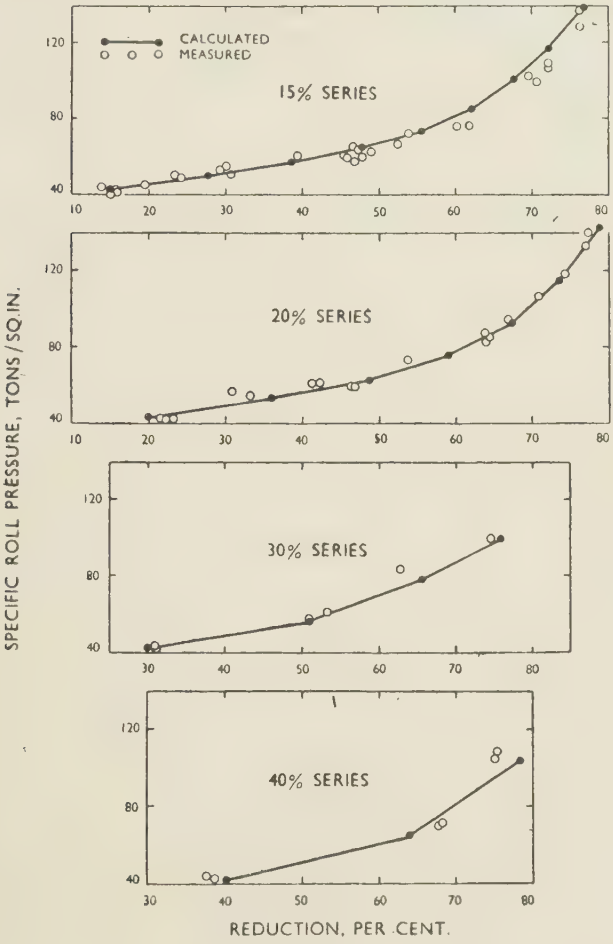



Fig. 7 (*continued*).

if the torque $T$ required to effect the reduction of the material only and the corresponding rolling load are measured, then :

$$T = 2P\beta e$$

and

$$\beta = \frac{T}{2Pe}$$

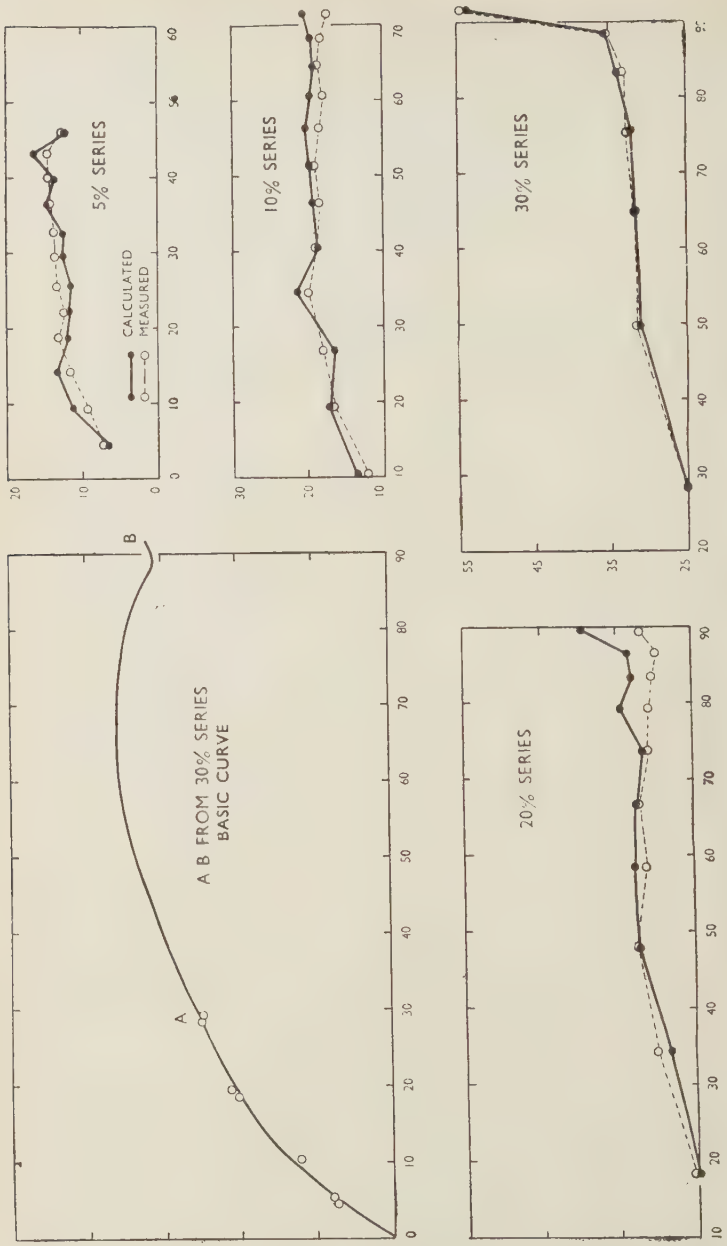



Fig. 8.—Annealed H.C. Copper, 3·0 in. Wide, 0·1 in. Initial Thickness. Roll surface: ground mirror finish (wheel grit 400).

Values of β for the measured results obtained when rolling the 0·2–0·25%-carbon steel and 0·1-in.-thick copper are recorded in Tables II and III respectively. It will be seen that, except for a slight drift, β can be considered constant, which accounts for the fact that the total-energy values plotted in Figs. 2 and 3 lie on smooth curves. In these tests, rolls having a ground mirror finish were used.

Table IV gives values of β for the 0·1-in. copper reduced on rolls with a ground matte finish. For this series of results, the constancy of β is not so good as that shown in Tables II and III, and accounts

TABLE II.—*Ratio of Lever Arm to Arc of Contact.*

0·2–0·25%-carbon electric-furnace steel, 3·0 in. wide × 0·1 in. thick.
Roll finish : ground mirror finish, wheel grit 400,
Calculated from Ford's torque and load measurements.

| Reduction, %. | 10. | 20. | 30. | 40. | 45. | 50. | 60. | 70. |
|---|---|---|---|---|---|---|---|---|
| 1st pass . | 0·42 | 0·39 | 0·42 | 0·43 | 0·42 | 0·43 | 0·42 | 0·35 |
| | 0·42 | 0·37 | 0·44 | 0·45 | 0·42 | 0·44 | 0·42 | 0·35 |
| 2nd pass . | 0·43 | 0·39 | 0·43 | 0·42 | 0·45 | 0·45 | ... | ... |
| | 0·45 | 0·39 | 0·42 | 0·43 | 0·44 | 0·43 | ... | ... |
| 3rd pass . | 0·43 | 0·40 | 0·41 | 0·38 | ... | ... | ... | ... |
| | 0·40 | 0·39 | 0·41 | 0·40 | ... | ... | ... | ... |
| 4th pass . | 0·37 | 0·36 | 0·39 | ... | ... | ... | ... | ... |
| | 0·38 | 0·36 | 0·37 | ... | ... | ... | ... | ... |
| 5th pass . | 0·41 | 0·36 | ... | ... | ... | ... | ... | ... |
| | 0·41 | 0·37 | ... | ... | ... | ... | ... | ... |
| 6th pass . | 0·37 | 0·40 | ... | ... | ... | ... | ... | ... |
| | 0·38 | 0·37 | ... | ... | ... | ... | ... | ... |
| 7th pass . | 0·40 | ... | ... | ... | ... | ... | ... | ... |
| | 0·40 | ... | ... | ... | ... | ... | ... | ... |
| 8th pass . | 0·34 | ... | ... | ... | ... | ... | ... | ... |
| | 0·36 | ... | ... | ... | ... | ... | ... | ... |
| 9th pass . | 0·36 | ... | ... | ... | ... | ... | ... | ... |
| | 0·34 | ... | ... | ... | ... | ... | ... | ... |
| 10th pass . | 0·38 | ... | ... | ... | ... | ... | ... | ... |
| | 0·35 | ... | ... | ... | ... | ... | ... | ... |

for the scattering of the points about the mean curve in Fig. 4. In spite of this, however, as will be seen later, when a comparison is made of the calculated and measured loads the above-mentioned assumption regarding the energy consumption and constancy of β is reasonable, even for rolls with a matte surface, because the agreement between calculated and measured loads is good for total reductions in one or more passes up to at least 60%.

## IV.—Construction of Basic Curves for Use with Equation (2).

In order to calculate rolling loads from equation (2), it is necessary to establish experimentally a curve relating the load developed during

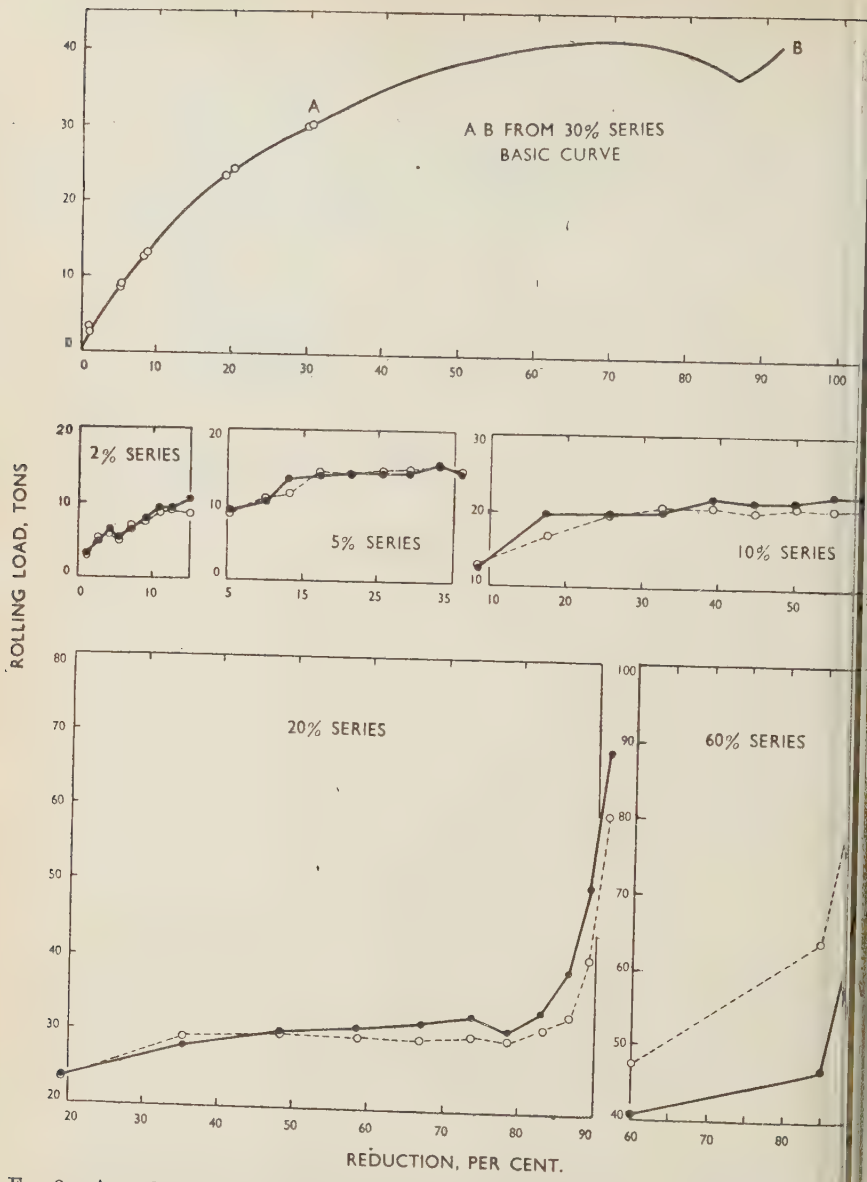
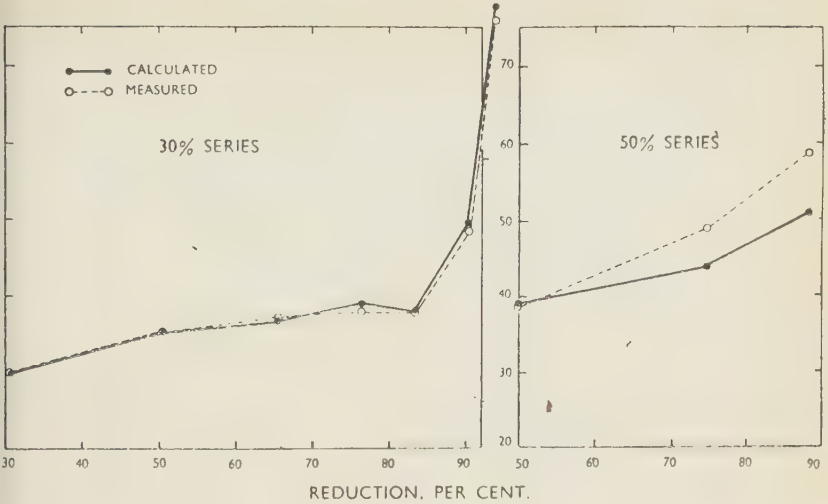



FIG. 9.—Annealed H.C. Copper, 3 in. Wide, 0·1 in. Initial Thickness. Roll surface: gro
dull matte finish (wheel grit 180).



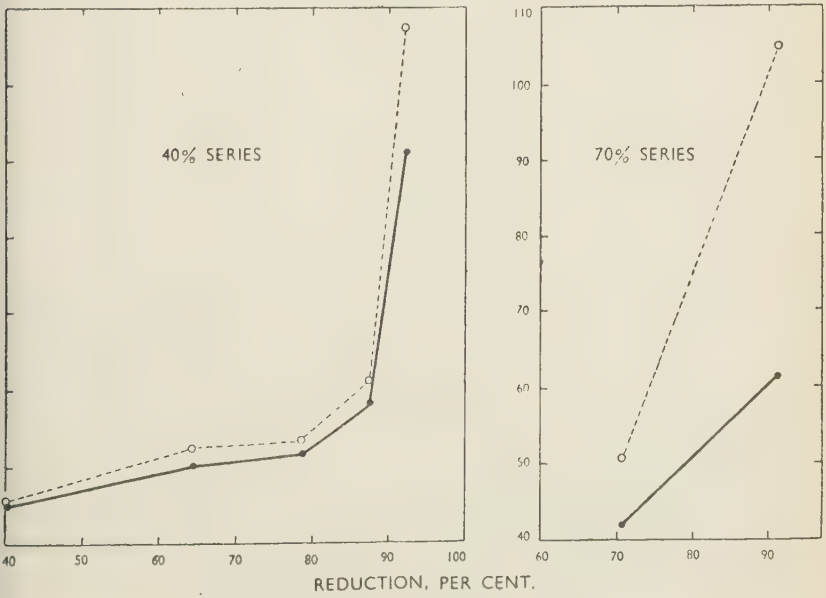




FIG. 9 (*continued*).

any one single pass to the percentage reduction in thickness effected. To be useful for practical applications, the first-pass basic curve should preferably cover reductions of 60–80%, for total reductions of this magnitude are not uncommon. Since, however, it is not usual to make such high reductions in one pass, it will be shown, by the use of equation (2), how the curve can be extended using experimental data determined from one particular series of progressive passes. The measured loads obtained when rolling 0·2–0·25%-carbon electric-furnace steel will serve to illustrate the procedure.

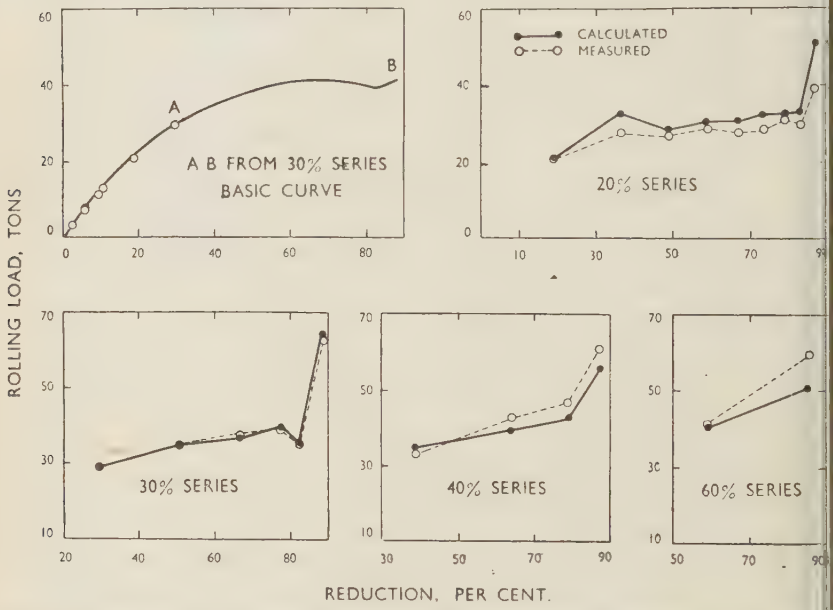



Fig. 10.—Annealed H.C. Copper, 3·0 in. Wide, 0·075 in. Initial Thickness. Roll surface ground dull matte finish (wheel grit 180).

Although numerical values can be determined very quickly from equation (2) by the use of a slide rule or, preferably, a small calculating machine, and tables of square roots, the computations can be much simplified by the use of Table V, in which values of $\sqrt{R}/(100 - R)$ are recorded and used in illustrating the derivation of the basic curve shown in Fig. 5. The measured loads for first passes of 5, 10, and 20% were first plotted as shown in Fig. 5 and the extension of the abscissa of this curve to a percentage reduction of 76% was made by using the load and percentage-reduction data determined when submitting samples initially reduced by 20% to a further five passes, each

approximately of 20% relative to the thickness before each pass. These results are recorded in the first four columns of Table VI.

With $R_1$ equal to 20·2, the value of the coefficient of $P_1$ in the first term of equation (2) can be read from Table V, i.e. when $R$ equals 20·2 :

$$\sqrt{R_1}/(100 - R_1) = 0{\cdot}0563,$$

TABLE III.—*Ratio of Lever Arm to Arc of Contact.*

Annealed H.C. copper, 3·0 in. wide × 0·1 in. thick.
Roll finish : ground mirror finish, wheel grit 400.
Calculated from Ford's torque and load measurements.

| Reduction, %. | 10. | 20. | 30. |
|---|---|---|---|
| 1st pass | 0·44 | 0·38 | 0·39 |
| | 0·41 | 0·43 | 0·38 |
| 2nd pass | 0·38 | 0·46 | 0·40 |
| | 0·43 | 0·44 | 0·40 |
| 3rd pass | 0·45 | 0·45 | 0·40 |
| | 0·40 | 0·41 | 0·37 |
| 4th pass | 0·40 | 0·41 | 0·38 |
| | 0·40 | 0·40 | 0·40 |
| 5th pass | 0·44 | 0·40 | 0·38 |
| | 0·43 | 0·36 | 0·41 |
| 6th pass | 0·37 | 0·34 | 0·41 |
| | 0·41 | 0·35 | 0·42 |
| 7th pass | 0·38 | 0·34 | 0·34 |
| | 0·38 | 0·34 | 0·28 |
| 8th pass | 0·45 | 0·36 | ... |
| | 0·41 | 0·37 | ... |
| 9th pass | 0·47 | 0·50 | ... |
| | 0·47 | 0·49 | ... |
| 10th pass | 0·41 | 0·32 | ... |
| | 0·44 | 0·31 | ... |
| 11th pass | 0·45 | ... | ... |
| | 0·44 | ... | ... |
| 12th pass | 0·51 | ... | ... |
| | 0·47 | ... | ... |

and since $P_1$ equals 45·0 tons, as measured, the first term on the left-hand side of equation (2) becomes :

$$P_1\sqrt{R_1}/(100 - R_1) = 2{\cdot}534,$$

i.e. $W_{n=1}$ in Table VI. For the second pass, the coefficient of $P_2$, equation (2), must be computed. The values of $R_2$ and $R_1$ are 36·8 and 20·2% respectively, and with $P_2$ the measured load for the second pass equal to 53·8, the second term of equation (2) becomes

$$P_2\sqrt{R_2 - R_1}/(100 - R_2) = 3{\cdot}468,$$

i.e. $W_{n=2}$ in Table VI. The value of $P_S$, i.e. the load which would be developed if the reduction $R_2$ of 36·8% had been accomplished in

one pass, is derived by dividing the sum of the first two terms, i.e. $W_1 + W_2$, by the coefficient of $P_S$ in equation (2), $n$ in this right-

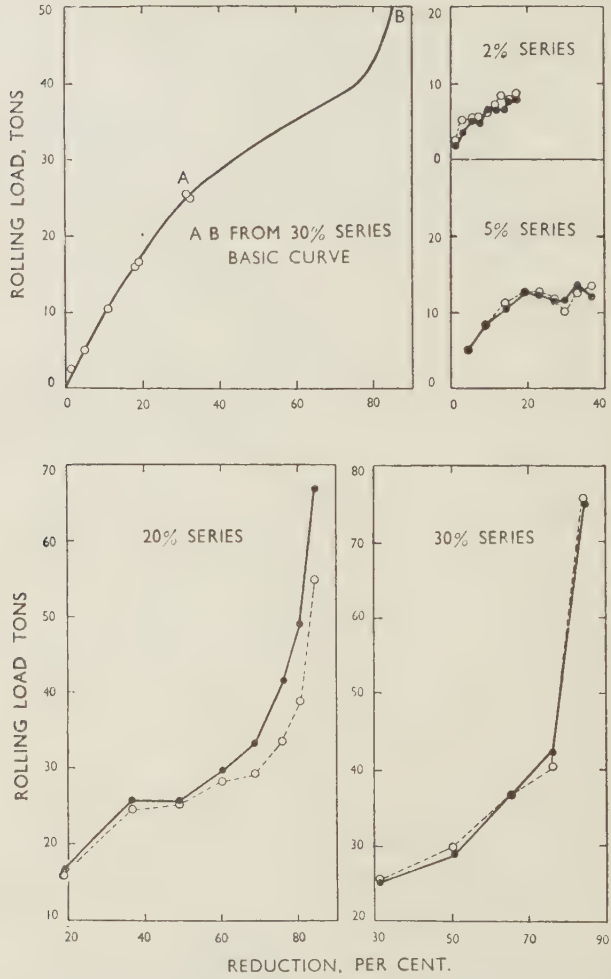



FIG. 11.—Annealed H.C. Copper, 3·0 in. Wide, 0·05 in. Initial Thickness. Roll surface: ground dull matte finish (wheel grit 180).

hand term now signifying the second pass. The value of this coefficient is read from Table V against $R$ equals 36·8, and is:

$$\sqrt{R_2}/(100 - R_2) = 0{\cdot}0960.$$

Hence :

$$_2P_S = (2{\cdot}534 + 3{\cdot}468)/0{\cdot}096 = 62{\cdot}5 \text{ tons.}$$

For the third pass, the third term on the left-hand side of equation (2) is :

$$W_3 = P_3\sqrt{R_3 - R_2}/(100 - R_3) = 4{\cdot}034,$$

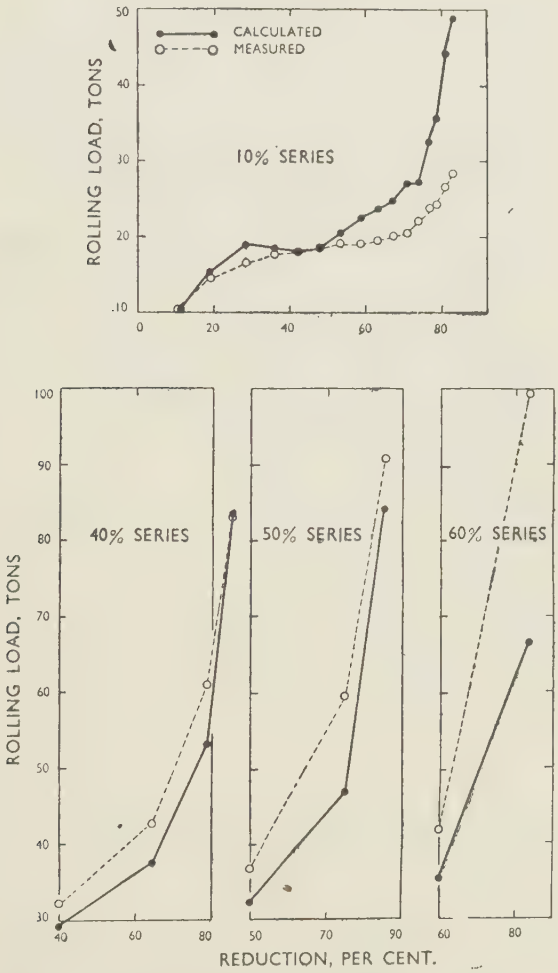



FIG. 11 (*continued*).

and the coefficient of the term on the right-hand side, as read from Table V for $R$ equals 49·4%, is :

$$\sqrt{R_3}/(100 - R_3) = 0{\cdot}1389.$$

Dividing the sum of $W_n$, i.e. $W_1 + W_2 + W_3$, corresponding to $n$ equals 3 in Table VI, gives :

$$_3P_S = 10{\cdot}04/0{\cdot}1389 = 72{\cdot}3 \text{ tons.}$$

The remaining values for the fourth, fifth, and sixth passes were computed in the same manner, the numerical results being given in Table VI.

TABLE IV.—*Ratio of Lever Arm to Arc of Contact.*

Annealed H.C. copper, 3·0 in. wide × 0·1 in. thick.
Roll finish : ground dull matte finish, wheel grit 180.
Calculated from Ford's torque and load measurements.

| Reduction, %. | 10. | 20. | 30. | 40. | 50. | 60. | 70. | 80. |
|---|---|---|---|---|---|---|---|---|
| 1st pass . | 0·36 | 0·33 | 0·33 | 0·37 | 0·37 | 0·37 | 0·36 | 0·35 |
| | 0·31 | 0·35 | 0·33 | 0·38 | 0·38 | 0·36 | 0·36 | 0·39 |
| 2nd pass . | 0·35 | 0·37 | 0·34 | 0·39 | 0·38 | 0·37 | 0·26 | ... |
| | 0·35 | 0·39 | 0·33 | 0·40 | 0·39 | 0·35 | 0·26 | ... |
| 3rd pass . | 0·32 | 0·36 | 0·34 | 0·34 | 0·32 | 0·22 | ... | ... |
| | 0·31 | 0·35 | 0·33 | 0·37 | 0·32 | 0·20 | ... | ... |
| 4th pass . | 0·28 | 0·35 | 0·35 | 0·31 | ... | ... | ... | ... |
| | 0·27 | 0·33 | 0·31 | 0·29 | ... | ... | ... | ... |
| 5th pass . | 0·29 | 0·31 | 0·34 | 0·19 | ... | ... | ... | ... |
| | 0·31 | 0·33 | 0·29 | 0·20 | ... | ... | ... | ... |
| 6th pass . | 0·26 | 0·32 | 0·22 | ... | ... | ... | ... | ... |
| | 0·28 | 0·32 | 0·21 | ... | ... | ... | ... | ... |
| 7th pass . | 0·30 | 0·29 | 0·15 | ... | ... | ... | ... | ... |
| | 0·24 | 0·29 | 0·16 | ... | ... | ... | ... | ... |
| 8th pass . | 0·24 | 0·28 | ... | ... | ... | ... | ... | ... |
| | 0·24 | 0·29 | ... | ... | ... | ... | ... | ... |
| 9th pass . | 0·26 | 0·23 | ... | ... | ... | ... | ... | ... |
| | 0·26 | 0·25 | ... | ... | ... | ... | ... | ... |
| 10th pass . | ... | 0·22 | ... | ... | ... | ... | ... | ... |
| | ... | 0·22 | ... | ... | ... | ... | ... | ... |
| 11th pass . | ... | 0·18 | ... | ... | ... | ... | ... | ... |
| | ... | 0·20 | ... | ... | ... | ... | ... | ... |

The first-pass loads $P_S$ were then plotted against the total percentage reduction, and thus the extension $AB$ of the basic first-pass curve given in Fig. 5 was obtained.

## V.—Comparison of Measured with Calculated Results.

The basic curves plotted in each of Figs. 5–11 were computed as described above; the values connected by full-line curves in the remaining diagrams in these figures have been calculated using the appropriate basic curves and equation (2). The results represented by small circles are Ford's measured loads. It will be realized that no

TABLE V.

| % $R$ | $\frac{\sqrt{R}}{100-R}$. | For Each 0·1% $R$, Add : | % $R$. | $\frac{\sqrt{R}}{100-R}$. | For Each 0·1% $R$, Add : | % $R$. | $\frac{\sqrt{R}}{100-R}$. | For Each 0·1% $R$, Add: |
|---|---|---|---|---|---|---|---|---|
| 0 | 0·0 | 0·00101 | ... | ... | ... | ... | ... | ... |
| 1 | 0·0101 | 0·00043 | 31 | 0·0807 | 0·00025 | 61 | 0·2003 | 0·00066 |
| 2 | 0·0144 | 0·00035 | 32 | 0·0832 | 0·00026 | 62 | 0·2072 | 0·00069 |
| 3 | 0·0179 | 0·00029 | 33 | 0·0858 | 0·00025 | 63 | 0·2145 | 0·00073 |
| 4 | 0·0208 | 0·00028 | 34 | 0·0883 | 0·00027 | 64 | 0·2222 | 0·00077 |
| 5 | 0·0236 | 0·00025 | 35 | 0·0910 | 0·00028 | 65 | 0·2303 | 0·00081 |
| 6 | 0·0261 | 0·00023 | 36 | 0·0938 | 0·00027 | 66 | 0·2389 | 0·00086 |
| 7 | 0·0284 | 0·00023 | 37 | 0·0965 | 0·00029 | 67 | 0·2480 | 0·00091 |
| 8 | 0·0307 | 0·00023 | 38 | 0·0994 | 0·00030 | 68 | 0·2577 | 0·00097 |
| 9 | 0·0330 | 0·00021 | 39 | 0·1024 | 0·00030 | 69 | 0·2680 | 0·00103 |
| 10 | 0·0351 | 0·00022 | 40 | 0·1054 | 0·00030 | 70 | 0·2789 | 0·00109 |
| 11 | 0·0373 | 0·00021 | 41 | 0·1085 | 0·00031 | 71 | 0·2905 | 0·00116 |
| 12 | 0·0394 | 0·00020 | 42 | 0·1117 | 0·00032 | 72 | 0·3030 | 0·00125 |
| 13 | 0·0414 | 0·00021 | 43 | 0·1150 | 0·00033 | 73 | 0·3165 | 0·00135 |
| 14 | 0·0435 | 0·00021 | 44 | 0·1185 | 0·00035 | 74 | 0·3308 | 0·00143 |
| 15 | 0·0456 | 0·00020 | 45 | 0·1220 | 0·00035 | 75 | 0·3464 | 0·00156 |
| 16 | 0·0476 | 0·00021 | 46 | 0·1256 | 0·00036 | 76 | 0·3633 | 0·00169 |
| 17 | 0·0497 | 0·00021 | 47 | 0·1294 | 0·00038 | 77 | 0·3815 | 0·00182 |
| 18 | 0·0518 | 0·00020 | 48 | 0·1332 | 0·00038 | 78 | 0·4014 | 0·00199 |
| 19 | 0·0538 | 0·00021 | 49 | 0·1373 | 0·00041 | 79 | 0·4233 | 0·00219 |
| 20 | 0·0559 | 0·00021 | 50 | 0·1414 | 0·00041 | 80 | 0·4472 | 0·00239 |
| 21 | 0·0580 | 0·00021 | 51 | 0·1458 | 0·00044 | 81 | 0·4734 | 0·00262 |
| 22 | 0·0601 | 0·00022 | 52 | 0·1502 | 0·00044 | 82 | 0·5035 | 0·00301 |
| 23 | 0·0623 | 0·00022 | 53 | 0·1549 | 0·00047 | 83 | 0·5357 | 0·00322 |
| 24 | 0·0645 | 0·00022 | 54 | 0·1598 | 0·00049 | 84 | 0·5728 | 0·00371 |
| 25 | 0·0667 | 0·00022 | 55 | 0·1648 | 0·00050 | 85 | 0·6150 | 0·00422 |
| 26 | 0·0689 | 0·00023 | 56 | 0·1701 | 0·00053 | 86 | 0·6622 | 0·00472 |
| 27 | 0·0712 | 0·00023 | 57 | 0·1756 | 0·00055 | 87 | 0·7173 | 0·00551 |
| 28 | 0·0735 | 0·00023 | 58 | 0·1813 | 0·00057 | 88 | 0·7814 | 0·00641 |
| 29 | 0·0758 | 0·00025 | 59 | 0·1873 | 0·00060 | 89 | 0·8576 | 0·00762 |
| 30 | 0·0783 | 0·00024 | 60 | 0·1937 | 0·00064 | 90 | 0·9487 | 0·00911 |

TABLE VI.

| Pass No. = $n$. | Reduction, %. | | Measured Load, tons = $P_n$. | Terms in Equation (2). | | Basic One-Pass Load, tons = $P_S$. |
|---|---|---|---|---|---|---|
| | Per Pass. | Total = $R_n$. | | Left Side $W_n$. | Right Side $W_S$ = sum of $W_n$. | |
| 1 | 20·2 | 20·2 | 45·0 | 2·534 | 2·534 | 45·0 |
| 2 | 20·8 | 36·8 | 53·8 | 3·468 | 6·002 | 62·5 |
| 3 | 20·0 | 49·4 | 57·5 | 4·034 | 10·04 | 72·3 |
| 4 | 20·7 | 59·9 | 60·0 | 4·848 | 14·89 | 77·2 |
| 5 | 20·4 | 68·1 | 60·2 | 5·405 | 20·30 | 78·4 |
| 6 | 32·6 | 78·5 | 96·5 | 14·475 | 34·78 | 84·5 |

physical significance attaches to the linking of these points by curves, which has been done only to facilitate comparison.*

For calculating the loads for passes subsequent to the first, equation (2) is used, and, as an example, the derivation of the points calculated for the 30% series, given in Fig. 5, is described below. The reductions obtained during the experimental rolling are included in Table VII.

The load corresponding to the first pass of 30% is read direct from the basic curve in Fig. 5, i.e. $P_1$ equals 56·0 tons. In order to determine

TABLE VII.

| Pass No. = $n$. | Reduction, %. | | $\sqrt{R}/(100 - R) = K$. Read from Table V. | Load Read from Basic Curve = $P_S$ tons. | $P_S K = W_S$. | Difference of $W_S$. | Load per Pass = $P_n$ tons. |
|---|---|---|---|---|---|---|---|
| | Per Pass. | Total $R$. | | | | | |
| 1 | 30·0 | 30·0 | 0·0783 | 56·0 | 4·385 | 4·385 | 56·0 |
| 2 | 30·4 | 51·3 | 0·1471 | 73·2 | 10·778 | 6·393 | 67·4 |
| 3 | 29·3 | 65·6 | 0·2352 | 78·1 | 18·350 | 7·572 | 68·9 |
| 4 | 30·1 | 75·9 | 0·3604 | 82·0 | 29·600 | 11·250 | 84·6 |

the value of the first term $W_1$ in equation (2), it is necessary to evaluate the factor $\sqrt{R_1}/(100 - R_1)$, and this, as read from Table V against $R$ equals 30, is 0·0783. Hence:

$$W_1 = 56 \times 0{\cdot}0783 = 4{\cdot}385 = {}_1W_S.$$

If the total reduction obtained after the second pass, i.e. 51·3%, is effected in one pass, then the load ${}_2P_S$ which would be developed is 73·2 tons as read from the basic curve, and the coefficient $\sqrt{R_2}/(100 - R_2)$ of ${}_2P_S$ on the right-hand side of equation (2) is read from Table V against $R$ equals 51·3. Hence:

$${}_2W_S = {}_2P_S\sqrt{R_2}/(100 - R_2) = 10{\cdot}778.$$

The load developed for the second pass, i.e. continuing a reduction of 30% to 51·3%, is, therefore:

$$P_2 = ({}_2W_S - {}_1W_S)(100 - R_2)/\sqrt{R_2 - R_1} = 67{\cdot}4 \text{ tons.}$$

When the total reduction effected in the three passes, i.e. 65·6%, is achieved in one pass, the load ${}_3P_S$ according to the basic curve is 78·1 tons, and the value of the term ${}_3W_S$ on the right-hand side of

* In Fig. 7, the ordinate is plotted as tons per square inch since there were insufficient data to convert the measured values into tons. Both in the experimental work and in the calculation, the values in tons per square inch were obtained by dividing the load by the nominal projected area of contact.

equation (2) is $78{\cdot}1\sqrt{65{\cdot}6}/(100 - 65{\cdot}6)$. Against 65·6 in Table V, the value of the factor multiplying 78·1 is 0·2352. Hence :

$$_3W_S = 18{\cdot}350.$$

The load $P_3$ developed when the reduction is increased from 51·3 to 65·6% is :

$$P_3 = (_3W_S - {}_2W_S)(100 - R_3)/\sqrt{R_3 - R_2} = 68{\cdot}9 \text{ tons.}$$

The load $P_4$ for the fourth pass is found in the same way.

The measure of agreement between the calculated and determined results is plainly shown in the various diagrams. In Figs. 5–7, in which the calculated and measured data for the three steels are plotted, it will be seen that the calculated values agree closely with all the experimentally determined results up to total reductions of 80%, even when this reduction is obtained by individual reductions each as high as 40%. The calculated and measured results recorded in Fig. 8 for the 0·1-in.-thick H.C. copper also show good agreement, except for some divergence at the last four passes in the 20% series, where the total reductions exceeded 75%.

The results for the three steels and the 0·1-in.-thick H.C. copper given in Figs. 5–8 were all obtained with rolls prepared with a mirror finish, and the good agreement between the calculated results and the measured values indicate the validity of the method for these rolling conditions.

In Fig. 9, details are given of the results obtained when rolling 0·1-in. copper on rolls with a dull matte surface, and it will be seen that the calculated results agree well with the measured results up to individual reductions per pass of 40%, even as far as total reductions of 90%. For the second and subsequent passes of the 50, 60, and 70% series, however, the computed results are lower than the measured values; but the calculated loads for the first pass of the same series are in better agreement. As for the 0·075 and 0·05 in. copper, Figs. 10 and 11 respectively, also reduced on rolls with a dull matte surface, agreement between the calculated and measured results is good until total reductions of 60% and individual reductions of 50% are exceeded.

## VI.—Applicability of the Method.

It will be appreciated that any one first-pass basic curve will refer only to the particular conditions obtaining during the determination of the curve, i.e. roll diameter, friction, and the initial thickness of the material being rolled. However, it is not necessary to establish individual first-pass curves separately for all diameter of rolls, initial

thicknesses, and friction conditions. It has been shown by the authors [8] that, for a given initial thickness and roll-surface condition, the relationship between the rolling load and the roll diameter is linear. If, therefore, basic curves are established for any given material for two widely different roll diameters, the data for any intermediate diameter can be interpolated. This conclusion is also supported by the experimental results of Emicke and Lucas [9] on the rolling of aluminium alloys.

The results of the computations already published,[8] and those of Emicke and Lucas, also show that, for any given roll diameter, the magnitude of the rolling load bears a linear relationship to the initial thickness within the range 0·5–0·1 in. For initial thicknesses less than 0·1 in. further experimental curves would be necessary, but the measurements of Emicke and Lucas and the authors' calculations referred to above indicate that two, or at the most three, curves would suffice for this range of initial thickness.

As the degree of roll-surface roughness, or smoothness, can be measured by methods developed in the last few years, it is possible that basic first-pass curves established for two- or three-roll finishes, representative of those used in normal rolling practice, could be used to construct curves for intermediate finishes. It is, however, realized that other factors as well as roll surface, such as lubrication and surface condition of the material being rolled, influence the frictional forces developed. In constructing a series of basic curves, advantage should also be taken of the principle of geometrical similarity, for if the ratio of the roll diameter to the original thickness of the material is constant, then the rolling load is directly proportional to the roll diameter or to the initial thickness, provided that the percentage reduction is constant and that the surface conditions in the roll throat are the same.

The basic curve for a given set of conditions covers not only the influence of the compressive characteristics of the material in its dependence on the frictional conditions, and thus of plane inhomogeneous deformation, but also that of roll-face distortion.

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# THE EFFECT OF SINGLE- AND MULTI-HOLE DIE EXTRUSION ON THE PROPERTIES OF EXTRUDED ALUMINIUM ALLOY BAR.* 1112

By L. NORTHCOTT,† D.Sc., Ph.D., Member, D. McLEAN,‡ B.Sc., Member, O. R. J. LEE,‡ M.Sc., Ph.D., Member.

Synopsis.

Longitudinal streaks on the surface of aluminium alloy components machined from extruded bar in BA 35 and D.T.D. 423A alloys were found to be associated with erratic circumferential strength. The streaks have been shown to be due to the flow structure originating in extrusion through multi-hole die plates, and the principles will apply to alloys generally. To investigate the problem fully, billets of the two alloys were extruded through die plates having 1, 2, 3, or 4 holes, all the multi-holes being symmetrically disposed about the centre. Transverse sections of bars extruded through multi-hole die plates showed a structure termed " radial flow ", converging to that portion of the surface marked by the streak; this structure was absent from bars extruded through single-hole die plates. Segregation of particle constituents was found near the periphery in the zone of radial flow and, consequently, the circumferential tensile properties of multi-hole material were inferior to those of single-hole bar. Small-scale experiments with lead–bismuth composites and coloured plasticine showed that the segregate originated from the axial zone of the billet; with a die plate having a single central hole, on the other hand, the axial segregate was confined to the axis of the single bar, where it is relatively harmless. Provision of a central hole in 3- and 4-hole die plates confined the segregate to the axis of the central bar, and this advantage has been confirmed by industrial trials.

## I.—Introduction.

At one period in the mass production of a conical component which was machined from extruded aluminium alloy bar, large numbers of components were under suspicion owing to their having a fan-shaped, streaky appearance (Fig. 1, Plate XI). In service, these components rotate at extremely high speeds and, it was considered, would be subjected to a high circumferential tensile stress. It was feared that the streakiness might indicate low circumferential properties, and this was found to be so by work described below, under " Preliminary Tests ".

The cylindrical bars from which the components were made were extruded through single- or multi-hole die plates, and multi-hole die extrusion was suspected as being responsible for the streakiness and circumferential weakness, which in some components was very marked. It thus became clear that the original problem was part of the general

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† Armament Research Department, Metallurgical Branch, Woolwich.
‡ Formerly Armament Research Department.

question of the effect of extrusion through different types of die plates. An investigation was therefore initiated into the effect of extrusion, through die plates having 1, 2, 3, or 4 holes, on the mechanical properties of the bars. The experimental work showed that in many instances there was a variation in properties along the length of the bar; consequently, most tests were repeated many times (as an extreme instance nearly 150 drift tests were carried out), but only mean results are given in the present paper, and the question of scatter is dealt with separately, since it assisted in deciding the cause of the variable properties. To check the conclusions reached from this part of the work, laboratory extrusion experiments were carried out and were later extended to full-scale industrial trials.

## II.—Preliminary Tests.

An anodized component having typical fan-shaped streaks is shown in Fig. 1 (Plate XI). The streaks were much more prominent after than before anodizing. Fig. 2 (Plate XI) shows that when a flat was machined on the side of the component parallel to the axis, the streaks revealed by etching were parallel to one another, and it was evident that the fanwise spread shown in Fig. 1 was due to the conical shape of the component.

To ascertain whether the streaks indicated any circumferential weakness, a group of 87 components in D.T.D. 423A alloy, some with and some without streaks, were "drift" tested by forcing a tapered and lubricated plug into their hollow interiors, thus expanding the component. At a particular load the component would burst with a longitudinal fracture; the fractures were either fibrous or laminated. Typical examples are shown in Figs. 3 and 4 (Plate XI). The bursting loads fell into two groups of high and low values, and Table I shows the connection with streakiness and type of fracture. It was not known which of the components were machined from single-hole bars and which from multi-hole bars.

Table I.—*Drift Tests on* 87 *Components.*

| Group. | Number of Components. | Number with Streaks. | Number without Streaks. | Number with Laminated Fracture. | Number with Fibrous Fracture. |
|---|---|---|---|---|---|
| High bursting load 4–5·2 tons* . . . | 46 | 5 | 41 | 7 | 39 |
| Low bursting load 1–2·5 tons* . . . | 41 | 40 | 1 | 41 | 0 |

* These figures are a function of circumferential tensile strength and ductility.

There is a clear connection between streaky appearance, low bursting load, and laminated fracture, but a few of the streaky components had high strength and broke with fibrous fractures, so that there was much scatter among the streaky components. The prominence of the streaks varied considerably from component to component, but bore little relation to the bursting load.

Transverse sections were prepared of seven of the above components and of four additional unbroken ones. Those which had the streaky surface appearance showed what will be referred to subsequently as "radial flow structure", but this was absent from the non-streaky bodies. Figs. 7 and 6 (Plate XII), respectively, show the structures of complete bars with and without radial flow. Micro-examination of the region of radial flow revealed segregation of particle constituents and, in unbroken components, sometimes also surface cracks (Fig. 5, Plate XI).

Longitudinal section through the streaks showed strings of particles of intermetallic compounds parallel to the pattern of streaks, which were evidently an etching effect occurring during anodizing and caused by the segregation. These tests established the association between the circumferential weakness, the radial flow structure, and the segregate near the surface; the responsible factor was concluded to be the employment of multi-hole die plates in the extrusion process.

1. *Examination of Bar Extruded Through* 1, 2, 3, *or* 4-*Hole Die Plates.*

Two alternative alloys were used for the component originating the investigation and, with the generous co-operation of the Northern Aluminium Company, Ltd. (D.T.D. 423A), and the British Aluminium Company, Ltd. (BA 35), bars of both alloys were obtained $1\frac{5}{16}$ in. dia., extruded through 1, 2, 3,* or 4-hole die plates and heat-treated to specification. For convenience in description, distinguishing terms such as 4-hole bar and 4-hole specimen will be used. The arrangement of holes in the die plates was similar to those shown in Figs. 12–15 (Plate XIII), referred to later; the significant feature was that the single hole was centrally placed, but in the multi-hole plates none of the holes was central. A set of bars $1\frac{3}{32}$ in. dia. was also supplied in BA 35 alloy, but, as the results of their examination were similar to those on the larger bars, only brief reference will be made to them. The specification compositions (%) are :

| | Cu. | Mn. | Mg. | Fe. | Si. | Ni. | Sb. |
|---|---|---|---|---|---|---|---|
| D.T.D. 423A : | 1 | 1 | 0·5–1·25 | 0·75 | 0·75–1·25 | 0·3 | ... |
| BA 35 : | 2·5–4 | 0·2 | 0·5–0·75 | | 1·2 | 0·05 | 0·3–1 |

* Only BA 35 was extruded through the 3-hole die plate.

The figures quoted represent maximum values except where a range is indicated.

TABLE II.—*Longitudinal Tensile Properties* (0·564 *in. dia. bar*).

| Specimen from | BA 35 Alloy. | | | | D.T.D. 423A Alloy. | | | |
|---|---|---|---|---|---|---|---|---|
| | Proof Stress, tons/in.². | Ultimate Tensile Stress, tons/in.². | Elongation, % on 2 in. | Reduction in Area, %. | Proof Stress, tons/in.². | Ultimate Tensile Stress, tons/in.². | Elongation, % on 2 in. | Reduction in Area, %. |
| 1-Hole bar | 11·0 | 19·7 | 24½ | 30½ | 25·6 | 27·5 | 11 | 24½ |
| 2-Hole bar | 11·5 | 21·7 | 19 | 24 | 22·9 | 25·6 | 14 | 28 |
| 3-Hole bar | 11·0 | 19·9 | 21 | 24½ | ... | ... | ... | ... |
| 4-Hole bar | 12·5 | 19·8 | 18 | 28 | 22·3 | 25·3 | 12·5 | 18 |

The measured longitudinal tensile properties are given in Table II, which shows little difference between bars from different die plates. The BA 35 alloy has the lower strength and yield ratio, but greater ductility.

### 2. *Structure.*

The macrostructures of transverse sections cut from the middle of the BA 35 bars are shown in Figs. 6–9 (Plate XII). The D.T.D. 423A bars were similar, but of smaller grain-size. The 1-hole bar (Fig. 6) is characterized by a central segregate and a uniform structure away from the centre. The 2-hole bar (Fig. 7) shows, near the surface, the radial flow structure in which a radial segregate always occurred (cf. Fig. 5). The 3-hole bar (Fig. 8) shows two positions of radial flow, corresponding to the two adjacent holes in the die plate; the segregate lies between these two positions and spreads over an arc, and is therefore less concentrated than in the 2-hole bar. The structure of the 4-hole bar (Fig. 9) is similar to that shown in Fig. 8, but the angle between the two positions of radial flow is greater, corresponding to the greater angle subtended by the two nearest holes in the die plate (cf. Figs. 14 and 15, Plate XIII). These structures show how, in multi-hole extrusion, flow through each hole is affected by flow through neighbouring holes, and it is easy to picture how the central billet segregate appears at the surfaces of extruded bars, due to flow over the edges of the die holes at the positions nearest the billet axis. The later experiments with composite model billets confirmed this.

### 3. *Drift Tests.*

These tests were similar to those applied previously to the components. A lubricated conical steel plug, of 10° half angle, was forced

into cylinders (1·5 in. long, 1·29 in. outside dia., 1·00 in. inside dia.) machined from the bar. The depth of penetration as well as the bursting load were measured. This load was sharply defined, and is a function of circumferential ductility as well as strength, since the former governs the depth of penetration which in turn governs the area of the test cylinder in contact with the plug and, hence, the total load sustainable. Six cylinders from each bar were tested, and mean results are given in Table III.

TABLE III.—*Drift Tests on Cylinders Machined from Bars.*

| Specimen from | Load to fracture, tons. | |
|---|---|---|
| | BA 35 Alloy. | D.T.D. 423A Alloy. |
| 1-Hole bar . . . | 3·6 | 3·9 |
| 2-Hole bar . . . | 1·7 | 1·8 |
| 3-Hole bar . . . | 1·8 | ... |
| 4-Hole bar . . . | 1·8 | 1·7 |

The circumferential properties of the 1-hole bar material are thus considerably superior to those of 2-, 3-, or 4-hole bars, between which there is little to choose. All the 1-hole cylinders had fibrous fractures, but all except one of the multi-hole cylinders (out of a total of 30) had laminated fractures, and all without exception broke in the region of radial flow. The similarity of the results as between the two alloys is due to the greater ductility of the BA 35 alloy counterbalancing the greater strength of the D.T.D. 423A alloy. There was a tendency for the bursting load to be lower for cylinders taken from the last part of the bar to be extruded. The 2-hole bar of BA 35 showed this effect the most. With the smaller bars, low results were obtained with cylinders from the rear part of the 1-hole bar; these results are referred to below.

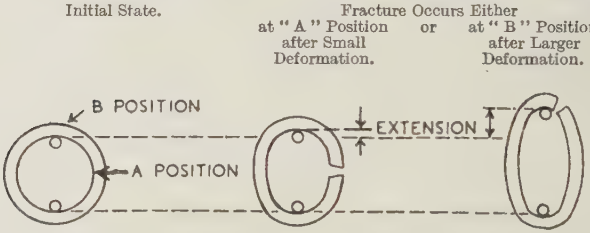
### 4. *Ring Tests.*

Another convenient test which applied circumferential stress to the outer layers of the bar was to take rings machined from the bars and apply a load by means of two $\frac{1}{8}$-in. dia. pins placed inside the rings. To appreciate the results, some discussion of the test is necessary, and it may be helpful to refer to the diagrams in Table IV. Preliminary tests showed that the stress distribution was complex and changed during the progress of the test. From the strain markings on polished rings, it was evident that during the early stages of the test the maximum tensile stress occurred on the inner surface of the ring midway between the pins (" A " position). If fracture took place without much deforma-

tion, it always did so from the inside outwards at this position. In a more ductile material, the position of maximum surface stress changed during the later stages of the test to the outside of the ring above the pins (" B " position). Fractures at this position always started from the outside of the ring. Consequently, with rings having a weak spot the orientation of this spot in relation to the pins affected the results. As a standard position it was natural to choose that which gave the lowest results. With the D.T.D. 423A rings this was with the radial flow at the " A " position. The BA 35 rings, however, owing to their greater ductility, would sometimes break at the " B " instead of the " A " position, whatever the orientation of the radial flow position. In the main tests six or ten rings from each bar were tested, the D.T.D. 423A rings with the radial flow in the " A " position, but the BA 35 rings were tested in various positions. The extension measured over the pin positions was recorded, as well as the load to fracture. The mean results are given in Table IV.

TABLE IV.—*Ring Tests.*

Each result the mean of six or ten tests.

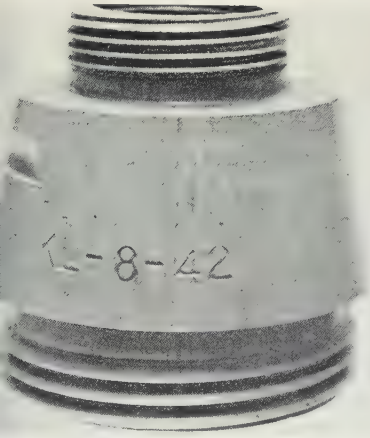


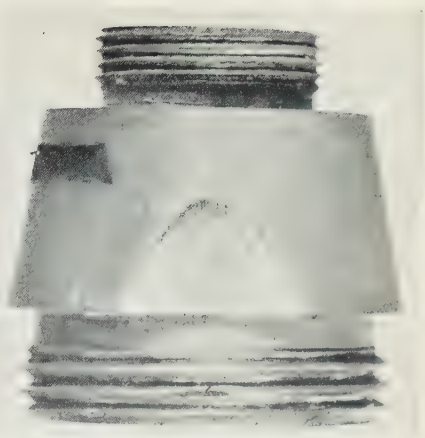

The loads to fracture and extensions are measures of circumferential strength and ductility.

| Ring from | BA 35 Alloy. | | D.T.D. 423A Alloy. | |
|---|---|---|---|---|
| | Load to Fracture, lb. | Extension, %. | Load to Fracture, lb. | Extension, %. |
| 1-Hole bar . . | 1230 | 51·7 | 3470 | 20·5 |
| 2-Hole bar . . | 840 | 32·9 | 1790 | 3·8 |
| 3-Hole bar . . | 830 | 47·0 | ... | ... |
| 4-Hole bar . . | 795* | 43·0 | 2040 | 12·4 |

* 865 if one very low value is omitted.

The marked superiority of the single-hole material is again shown. Among the results on multi-hole rings, those from 3- or 4-hole bar are



2

Figs. 1 and 2.—Components Showing Fan-Shaped Streaks, Parallel on Machined Flat. · $1\frac{1}{2}$.



FIG. 3.—Fibrous Fracture of 1-Hole Cylinder. × 3.

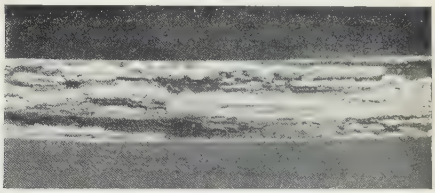


Fig. 4.—Laminated Fracture of 2-Hole Cylinder. × 3.



FIG. 5.—Transverse Section at Periphery of 2-Hole Bar in Radial Flow Position. Cracks and radial segregates. × 50.

[*To face p.* 86.

Etched Transverse Sections of Extruded Bars. × 1½.

Fig. 6.
1-Hole.



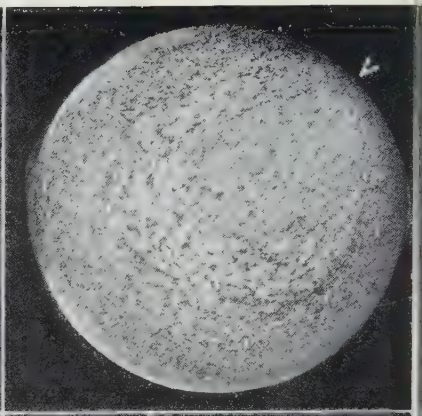
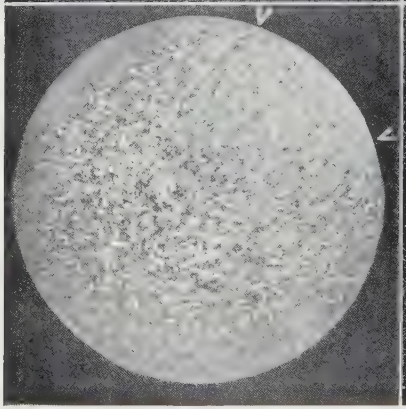
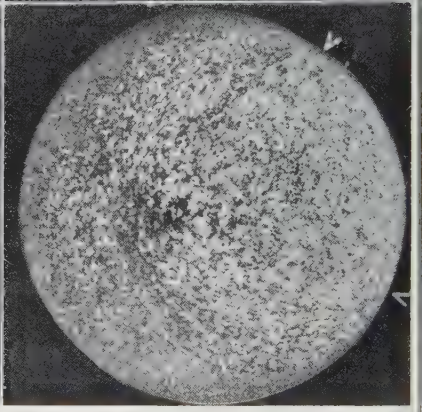


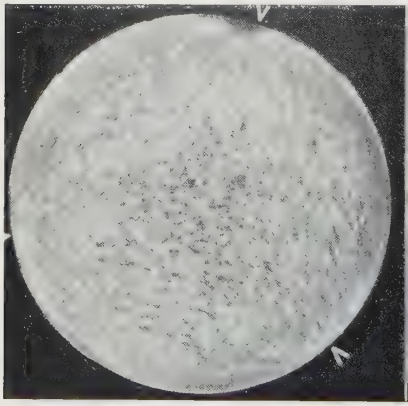
Fig. 8.
3-Hole.

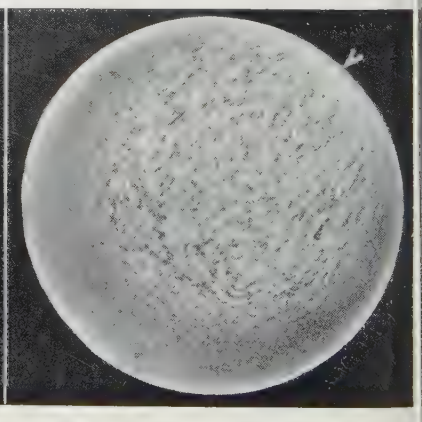




FIGS. 6–9.—BA 35 Bars Extruded Through 1- to 4-Hole Die Plates Similar to Those in Figs. 12–15.

Fig. 10.





Centre Bar. Outer Bar.

FIGS. 10 and 11.—D.T.D. 423A Bars Extruded Through a 4-Hole Die Plate Similar to that in Fig. 17.

Extrusion of Plasticine Billets Through Various Die Plates.

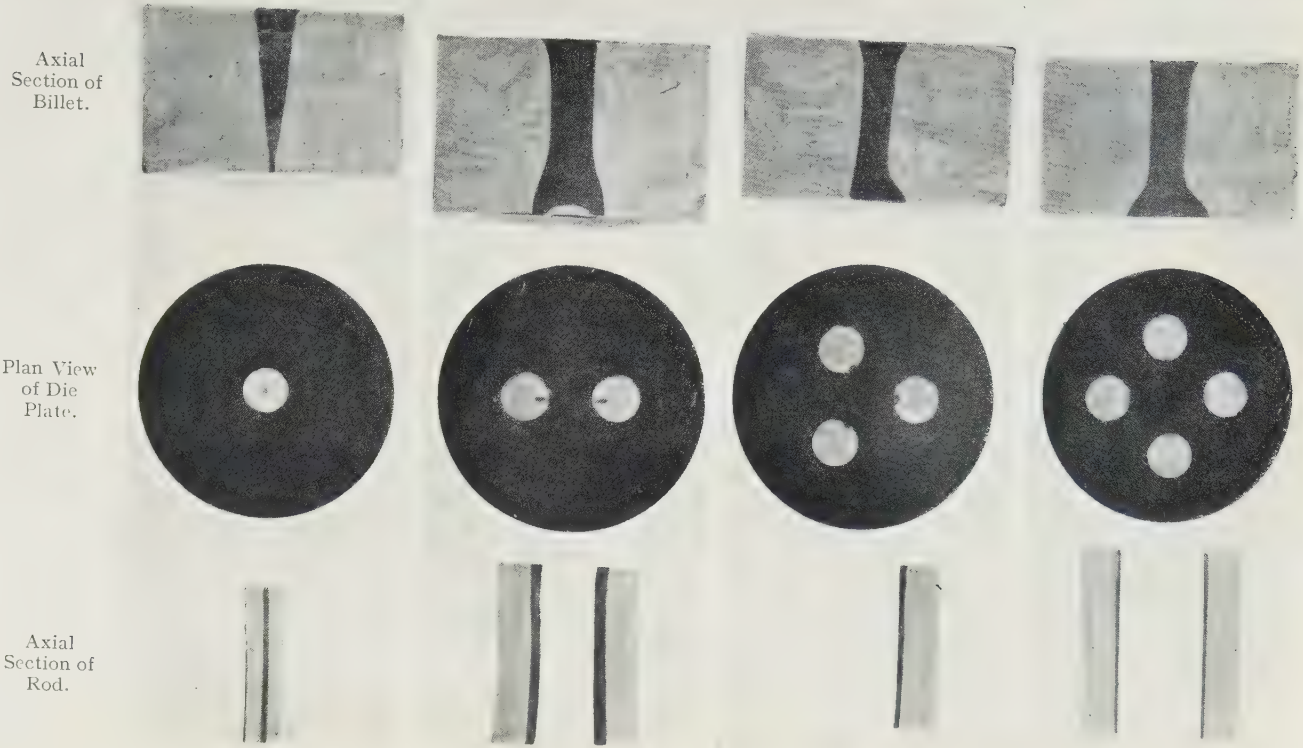


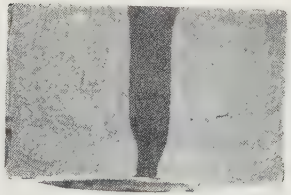

Fig. 12.—1-Hole.

Fig. 13.—2-Hole.

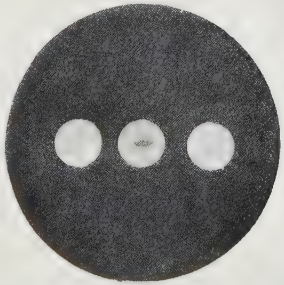
Fig. 14.—3-Hole.

Fig. 15.—4-Hole.

Axial Section of Billet.



Plan View of Die Plate.



Axial Section of Rod.

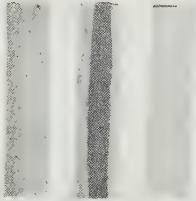
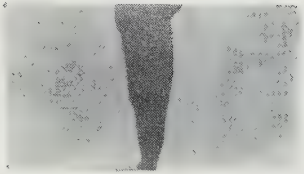


FIG. 16.—3-Hole with Central



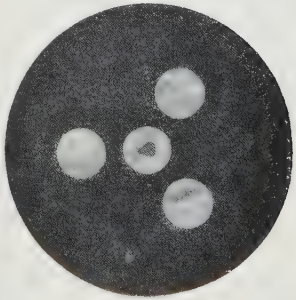




Fig. 17.—4-Hole with Central

superior to those from 2-hole bar, except for the fracture loads of the BA 35 rings.*

Out of 34 fractures through the radial flow, 25 were laminated, but all fractures which did not pass through the radial flow were fibrous.

### 5. *Tensile Tests on Circumference.*

Rings prepared as above from the 1-, 2-, and 4-hole bars in D.T.D. 423A alloy were cut through at one point, straightened out hot, and re-heat-treated (10 hr. at 525° C.; water quenched; aged for 12 hr. at 160°–170° C.). Straight tensile tests then measured the circumferential tensile properties of the outer layers of the original bar. By making the cut either through the radial flow position or diametrically opposite, the properties outside or inside the radial flow zone could be compared; average results are given in Table V.

TABLE V.—*Circumferential Tensile Tests* (0·1-*in. Square Bars of D.T.D.* 423A *Alloy*).

| Specimen from | Radial Flow in Gauge-Length. | Ultimate Tensile Strength, tons/in.². | Elongation, %. | Type of Fracture. |
|---|---|---|---|---|
| 1-Hole bar . | absent | 24·3 | 9 | fibrous |
| 2-Hole bar { | yes | 22·9 | 4 | laminated |
| | no | 23·7 | 9 | fibrous |
| 4-Hole bar { | yes | 23·6 | 6 | laminated |
| | no | 24·6 | 10 | fibrous |

Two conclusions are obvious. Away from the radial flow position the circumferential properties of multi-hole die material are as good as those of single-hole die material, but in the radial flow position the properties, especially ductility, are inferior. In this position the 4-hole die material is superior to the 2-hole material. All fractures through the radial flow positions were laminated.

### 6. *Explanation of the Variation in Circumferential Properties of Multi-Hole Bars.*

The only peculiarities of the material in the radial flow position are the macrostructure (radial flow) and the segregate of intermetallic compounds near the surface; circumferential weakness in this position must consequently be explicable in terms of these two factors. Now the macrostructure was constant over long lengths of each bar, whereas

* It is suspected, however, that the latter are affected by the possibility of breaking at either the " A " or " B " position since owing to the angular spread of the circumferential weakness in the 3- and 4-hole material (shown by the structures), with any given orientation, fracture has more chance of finding a weak spot.

the intensity of segregation varied, and a study of the circumferential properties showed that they also varied along the length of each bar. This is expressed in Table VI, in which are given the maximum and minimum values in the different tests and their ratios, including—for multi-hole material—only those tests where fracture occurred in the radial flow position. Results from 48 drift tests on finished components specially made from 1-, 2-, 3-, and 4-hole bars of BA 35 alloy are also included.

TABLE VI.—*Variation in Circumferential Properties.*

(For multi-hole material only, tests in which fracture occurred through the radial flow position are considered.)

| Sample. | | BA 35 Alloy. | | | | | D.T.D. 423A Alloy. | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Ring Tests. | | Drift Tests on Cylinders. | | Drift Tests on Components.* | Ring Tests. | | Drift Tests on Cylinders. | |
| | | Load, lb. | Extn., %. | Load, ton. | Ductility, cm. Penetration. | Load, tons. | Load, lb. | Extn., %. | Load, tons. | Ductility, cm. Penetration. |
| 1-Hole bar | max. | 1410 | 53 | 7·50 | 3·9 | 4·75 | 3850 | 21 | 4·84 | 2·2 |
| | min. | 970 | 50 | 3·02 | 1·7 | 3·25 | 3090 | 18 | 2·58 | 1·2 |
| | ratio | 1·43 | 1·06 | 2·5 | 2·3 | 1·4 | 1·2 | 1·2 | 1·9. | 1·8 |
| 2-Hole bar | max. | 1260 | 50 | 2·62 | 1·7 | 3·45 | 2420 | 14 | 1·88 | 0·8 |
| | min. | 295 | 34 | 0·92 | 0·3 | 0·9 | 1660 | 3 | 1·86 | 0·5 |
| | ratio | 4·3 | 1·5 | 2·6 | 5·7 | 3·8 | 1·5 | 4·7 | 1·01 | 1·6 |
| 3-Hole bar | max. | 1140 | 50 | 2·36 | 1·1 | 3·45 | ... | ... | ... | ... |
| | min. | 265 | 38 | 1·08 | 0·5 | 1·75 | ... | ... | ... | ... |
| | ratio | 4·2 | 1·3 | 2·2 | 2·2 | 2·0 | ... | ... | ... | ... |
| 4-Hole bar | max. | 1100 | 49 | 3·77 | 1·8 | 3·15 | 2860 | 20 | 1·85 | 0·85 |
| | min. | 185 | 28 | 0·95 | 0·4 | 1·75 | 1660 | 8 | 1·65 | 0·6 |
| | ratio | 5·9 | 1·7 | 4·0 | 4·5 | 1·8 | 1·7 | 2·5 | 1·1 | 1·2 |

* Different samples from those covered by Table I, for which the individual extrusion practice was unknown.

In general, there is greater variability in multi-hole than in single-hole material, particularly with the BA 35 alloy, and this variability must therefore be due to the variation in segregation.

Table VI brings out the further point that, whereas in single-hole material the properties vary from moderate to good, for multi-hole material they vary from moderate to bad. Since, in an alloy free from an intergranular constituent, the tensile strength measured transversely across a columnar crystal aggregate is greater than that measured in the direction of growth,[1] the circumferential strength should be raised by the radial flow structure. On the other hand, the segregate would be expected to weaken the material. Consequently, both because the disturbing factor is erratic and because it weakens the material, the

segregate must be held responsible for the variation in the circumferential properties of the multi-hole bars.

Micro-examination of multi-hole specimens showed a tendency for low loads to be associated with pronounced segregation of the particle constituents, but the correlation was not complete. This was not unexpected, since micro-examination covers only a two-dimensional surface whereas the mechanical properties are determined by the three-dimensional volume.

An opportunity to test the connection more conclusively and in the absence of the radial flow structure was provided, however, by the rear part of the smaller single-hole bar of BA 35 which, as previously mentioned, broke in the drift and ring tests at low loads, the fractures being mostly laminated. Micro-examination of these specimens revealed a dense longitudinal string of particles several inches long in the zone of fracture, but no radial flow. From an adjacent portion of the bar, two series of six rings were prepared of somewhat modified dimensions such that this segregate occurred close to the inside edge in one series, but in the other series the internal diameter was too great to include the segregate (the thickness of both series of rings being the same). Micro-examination after fracture confirmed that this intention was realized. For the tests, the rings were oriented so that the line of segregate was at the " A " position (see Table IV). Five of the six smaller rings broke at the segregate, the fracture being of the laminated type, but all six of the larger rings broke at the pin with a completely fibrous fracture. The fracture loads and ductilities of the smaller rings were much the more erratic :

| | Loads, lb. | | Extension, %. | |
|---|---|---|---|---|
| | Range. | Mean. | Range. | Mean. |
| Rings containing segregate . | 175–1040* | 845 | 30–54 | 46 |
| Rings not containing segregate | 910–1140 | 1070 | 48–59 | 56 |

* Or 1100 lb. if the ring which did not break in the segregate is included.

Bad segregation alone, without radial flow, can thus produce a drastic weakening of the material, confirming the previous conclusion that the surface segregate is the variable weakening influence in bars extruded through multi-hole dies.

### 7. *Depth of Circumferential Weakness.*

Tests on drift cylinders of different diameters, but of the same thickness, were made to discover how far below the surface of the bar the

harmful effects of segregation were evident. Any multi-hole cylinder too small to include the surface segregate should have a bursting load equal to that of a single-hole cylinder of similar size. To avoid confusion in interpreting the results, it should be noted that in a homogeneous material, such as single-hole bar, the bursting load will decrease with decreasing cylinder diameter, since the maximum percentage circumferential extension increases for a given area of contact with the plug. Table VII shows results for 1-, 2-, and 4-hole bars of D.T.D. 423A alloy.

TABLE VII.—*Influence of Drift Cylinder Diameter on Bursting Load.*

Cylinders, all $\frac{1}{8}$ in. thick, from $1\frac{5}{16}$-in. dia. bar of D.T.D. 423A alloy.

| Cylinder from | Load (tons) to Break Cylinders of Outside Diameters: | | | | |
|---|---|---|---|---|---|
| | 1·05 in. | 1·12 in. | 1·19 in. | 1·25 in. | 1·30 in. |
| 1-Hole bar . . | 1·4 | 2·3 | 2·15 | 4·0 | 3·0 |
| 2-Hole bar . . | 1·0 | 1·05 | 0·8 | 0·85 | 0·9 |
| 4-Hole bar . . | 1·25 | 1·25 | 1·3 | 1·6 | 1·7 |

Although the reduction in bursting load with diameter of single-hole cylinders is clearly shown, the relevant point is that with cylinders of 1·05 in. dia., multi-hole material has a breaking load almost as high as single-hole material. It will be seen that the weak zone penetrates to a depth of about $\frac{1}{8}$ in. below the surface and is more harmful in 2-hole than in 4-hole bar.

## III.—EXPERIMENTAL EXTRUSION.

Laboratory experiments were made to investigate the process of extrusion flow more fully, with the final aim of eliminating any surface segregation in multi-hole bars.

In extrusion the type of flow is much the same for most metals and is unaltered by the temperature or rate of extrusion, although these, of course, affect the mechanical properties of the extruded rod. Composite billets of lead and bismuth, and later of differently coloured plasticine, were used. Both models gave the same results, so reference will be confined to the plasticine as the structures obtained could be readily photographed.

Billets $2\frac{1}{2}$ in. long by $1\frac{1}{2}$ in. dia. were prepared with a $\frac{1}{4}$-in. dia. cylindrical core of different colour extending the full length of the billet. These billets were then extruded through various dies containing from 1 to 4 holes, and the extruded rod and remaining unextruded part of the

billet examined. Approximately 1 in. of the billet was left unextruded, and this portion was sectioned longitudinally; 1-in. lengths of the rods were also sectioned longitudinally in the same way as the billet and, finally, the rods were cut out flush with the face of the die and the die face, billet, and rods photographed (Figs. 12–15, Plate XIII).

Examination of the extruded rods showed that the size and shape of the portion from the core of the billet were the same over almost the full length of the rod; only at the front end of the rods was there any variation, a steady condition being reached within a few inches. With the 1-hole die, the central billet segregate was still central in the rod. With the multi-hole dies the billet segregate appeared near the surface of the rods, cutting through the surface at the position nearest the axis of the billet. Figs. 13–15 (Plate XIII) show that, as the number of die holes increases from 2 to 4, the segregate distribution changes from a radial to a peripheral form and, in addition, penetrates to a smaller depth below the surface of the bar. The segregate thus becomes more diffuse, and is likely to be less harmful in 4-hole than 2-hole bat. These results link up convincingly with the flow and segregation observed with the aluminium alloys.

Two other multi-hole die plates were tried with the plasticine model. The resultant photographs are reproduced in Figs. 16 and 17 (Plate XIV), which show the arrangement of holes. The significant feature is that one hole is central, and it is clear that the billet segregate is now concentrated in the core of the central rod. In this position it would be harmless for many applications and would be wholly removed in machining out hollow components.

This result prompted a similar experiment on an industrial scale, which was carried out by the Northern Aluminium Company, Ltd., using D.T.D. 423A alloy. A modified 4-hole die plate was used, similar to that in Fig. 17, i.e. 3 holes were at the corners of an equilateral triangle with the fourth hole in the centre. Lengths of the four $1\frac{5}{16}$-in. dia. bars extruded through this die plate were examined. A preliminary investigation showed the three outer bars to be similar, so a full examination was restricted to one outer bar and the central bar.

The macrostructures are shown in Figs. 10 and 11 (Plate XII), which reveal the radial flow structure in the expected positions. The microstructures, however, showed fewer intermetallic particles in these positions than in the previous multi-hole bars.

Drift tests were made on cylinders exactly as before with the following results:

| | |
|---|---|
| Central hole bar . . . | 2·1 tons bursting load. |
| Outer hole bar . . . | 2·0 „ „ „ |

Comparison with Table III shows these results to be better than with the previous multi-hole material, but inferior to the single-hole material.

Tensile tests were also performed as before on sawn rings straightened out hot and heat-treated (1 hr. at 535° C., water quenched, and aged for 5 hr. at 160° C.). A $\frac{3}{4}$-in. gauge length of reduced section ($\frac{1}{8}$ in. × $\frac{1}{8}$ in.) was machined centrally to include the radial flow position in some specimens and exclude it in others. The results are given in Table VIII.

TABLE VIII.—*Circumferential Tensile Tests on Experimental Bars.*

D.T.D. 423A alloy extruded through die of type shown in Fig. 17 (Plate XIV). 0·125-in. square bars.

| Bar. | Radial Flow in Gauge Length. | Ultimate Tensile Strength, tons/in.². | Elongation, %. | Type of Fracture. |
|---|---|---|---|---|
| Central | yes | 24·9 | 8 | laminated |
| | no | 29·0 | 10 | fibrous |
| Outer | yes | 25·7 | 8 | laminated |
| | no | 26·3 | 10 | fibrous |

Comparison with Table V shows that the properties of these bars were more uniform around the circumference and were better in the radial flow position than the previous multi-hole bars. The properties in the radial flow position were, however, still inferior to those of the previous single-hole bar.

On the assumption that the billets extruded for this and the previous work were similar with regard to degree of casting segregation, this arrangement of holes in the die plate gives better circumferential properties than the usual one, although the improvement is not apparently as great as the plasticine model might indicate. The method is, however, considered promising.

## IV.—CONCLUSIONS.

(1) The circumferential tensile properties of bar extruded through a die plate having a single central hole are superior to those of bar extruded through any multi-hole die plate.

(2) The explanation put forward is that the central segregate of the original billet remains central in the single-hole bar, but is extended radially and is displaced laterally to a position at the surface of multi-hole bars (Fig. 5, Plate XI), where, under circumferential strain, it causes laminated fracture after relatively small deformation.

(3) Extrusion through multi-hole dies causes radial extrusion flow (Figs. 7–11, Plate XII) at one or more positions on the circumference of

the bars, but this does not appear to be a serious matter in the absence of segregation.

(4) With multi-hole die plates, the holes are normally symmetrically disposed, but improvement is obtained by placing one hole at the centre of the die plate. The billet segregate then tends to be confined to the axis of the central bar.

(5) The structural features observed in the two aluminium alloys examined have been closely reproduced by materials having such different properties as lead–bismuth composites and plasticine, and should consequently apply generally to extruded materials.

Acknowledgements.

Thanks are due to the Northern Aluminium Company, Ltd., Banbury, and the British Aluminium Company, Ltd., Warrington, without whose co-operation the large-scale extrusion trials would not have been possible, and to Mr. S. Turner for help in the experimental work.

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# STRIATIONS: METALLOGRAPHIC EVIDENCE OF SLIP.* 1113

By D. McLEAN,† B.Sc., Member.

Synopsis.

Regular criss-cross "striations" (Fig. 2, Plate XV) have been observed under the microscope in lightly deformed brass on sections electrolytically polished and suitably etched. It is shown that the "striations" are sections through glide planes that have slipped, and probably indicate non-uniform deformation on these planes. Failure to observe these markings before has probably been due to the imperfections of mechanical polishing.

## I.—Introduction.

It is well known that slip lines can be seen on polished surfaces of a deformed metal if the metal is polished before deformation. Strain lines (Fig. 1, Plate XV) can also be seen on etched sections prepared after deformation when the deformation exceeds about 20%; the relation between strain lines and slip lines is uncertain. However, it seems to be believed that no evidence of slip or, indeed, of any microstructural change apart from slight elongation of the crystals, can be seen in a lightly deformed metal on a section polished and etched after deformation.[1, 2] This belief is shown in the present paper to be incorrect since markings which are evidence of slipped planes can be seen in brass when a suitable polishing and etching technique is adopted.

These markings differ observationally from strain lines (Figs. 1 and 12, Plates XV and XVI) in not being revealed by electrolytic etching, in being more numerous and practically straight, and, as appears later, in developing at much lower deformation.

Since the bulk of this research was completed, a paper by Jacquet [3] has been received describing, among other things, markings similar to those considered here and which Jacquet also ascribes to slip. The present paper gives further information on the nature of the markings, and deals mostly with brass instead of copper.

## II.—Experimental.

The 70 : 30 brass used for this work was prepared from electrolytic copper and electrolytic zinc.

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† Metallurgy Division, National Physical Laboratory, Teddington; formerly Armament Research Department, Woolwich.

The criss-cross markings which are the subject of this paper are shown in Fig. 2 (Plate XV); they had previously been observed in electrolytically polished 70 : 30 brass after etching.[4] They are referred to subsequently as " striations ". They were revealed best by etching in alkaline copper ammonium chloride solution or in hot, very dilute orthophosphoric acid, poorly by etching in ammonium persulphate in ammonia solution, and not at all by electrolytic etching in the electrolytic-polishing solution of orthophosphoric acid.

After prolonged electrolytic polishing to remove a layer about $\frac{1}{4}$ mm. thick, the striations did not reappear on etching if the specimen had been furnace cooled, but sometimes did so if it had been water quenched. They sometimes did reappear, however, if the specimens were re-filed, polished, and etched, and could again be removed by prolonged polishing. This suggested that the striations were due to deformation during preparation and that this deformation penetrated to a depth of nearly $\frac{1}{4}$ mm.

After hand polishing instead of electrolytic polishing, the criss-cross pattern could only be detected in disordered fragments. It could be definitely observed under the microscope but did not reproduce well. The appearance differed from Fig. 2, much as a disorderly array of bricks differs from the regular array in a brick wall. It seems likely that this is evidence of the surface distortion produced by hand polishing.

### 1. *Connection Between Striations and Slip Lines.*

Small cubes (1 cm. side), ascertained to be free from striations, were polished, and reduced about 4% by cold hammering. Photographs of slip lines were taken at various positions. The surface was then electrolytically polished to a depth of 0·001 cm., etched, and the same positions re-examined. Compared with the number of slip lines, very few striations were found, but these were always parallel to the corresponding slip lines, and where they were few enough to be picked out individually, were the same distance apart as certain of the slip lines (see Figs. 3 and 4, Plate XV).

These specimens were reduced an additional 4% and the same fields re-examined without further preparation. In all fields, some lines parallel to the striations now stood out far more prominently. Fig, 5 (Plate XV) shows the original striations in one field, and Fig. 6 (Plate XV) is a photograph under the interference microscope of the same field after the further cold work. The sharp steps in the interference fringes at the prominent lines show that further slip has occurred there, for before the extra deformation the interference fringes were

smooth at these points. The further slip has occurred on planes parallel to the striations.

From the foregoing it is concluded that striations mark the intersection of the polished surface with slip planes, and probably are thin regions along those that have actually slipped.

2. *Connection Between Striations and General Deformation.*

(*a*) Several cubes were annealed, furnace cooled, and reduced in thickness 2, 4, 8, 16, and 30% respectively by cold hammering. These samples, together with one unworked cube, were electrolytically polished, a layer $\frac{1}{4}$ mm. thick being removed to exclude surface deformation, and then etched. No striations were found in the undeformed specimen, but some were visible in the one deformed 2%, and their intensity and regularity increased to a maximum in the specimens deformed 4 and 8%; the striations were less distinct in the specimens deformed 16 and 30%, in which there were also strain lines.

(*b*) In a second experiment, a tapered specimen annealed and furnace cooled, was electrolytically polished and loaded in tension so as to produce 40% permanent elongation at the narrow end but none at the wide end. Transverse scribed lines permitted elongation determinations. The polished surface was then examined for slip lines, and a longitudinal section, after electrolytic polishing and suitable etching, for striations. Photographs of the latter are reproduced in Figs. 8–11 (Plate XVI). Starting at the wide end and moving towards the narrow end, neither slip lines nor striations were found in the undeformed region, Fig. 8. They were both first detected at the same point along the length of the specimen in the region of $\frac{1}{4}$% elongation (Fig. 9): the striations were short wisps projecting from the crystal boundaries, whereas the slip lines extended across entire crystals. With increasing deformation, each striation became more complete but never seemed to traverse an entire crystal, and more striations appeared, at first parallel to the original ones, but later, at about 3% elongation and coincident with the appearance on the polished exterior surface of a second set of slip lines, in another direction (Fig. 10). The second set became complete in a small proportion of crystals at 9% elongation (Fig. 11), coincident with the completion of the second set of slip lines in a similar small proportion of crystals. At higher deformation, a third set of slip lines and striations formed, and some striations became more prominent and curved.

These experiments confirm that striations are caused by deformation and that they are connected with slip. The growing prominence and continuity with increasing deformation up to 9% is ascribed to

repeated slip on the same plane.* For any degree of deformation, visible slip lines are much more numerous than striations.

### 3. *Connection Between Striations and Strain Lines.*

In the tapered tensile specimen, some striations became more prominent and curved with increasing deformation until they were ordinary strain lines; the structure in Fig. 11 gave way to that in Fig. 12 (Plate XVI). Definite strain lines were first seen at about 15% elongation. Examination of the cube deformed 30% showed no definite strain lines parallel to striations, but some instances were found of strain lines in one direction superimposed on a background of striations in two other directions. These might have been the remains of a third set of striations in the direction of the strain lines, but it is surprising that no other trace of such a set could be seen. The evidence about the connection between striations and strain lines is thus inconclusive, but the most likely hypothesis is that strain lines are an extreme form of striation, the atomic misalignment having become sufficient for the lines to be easily revealed by etching, and enough slip in other directions having occurred for the lines to be curved.

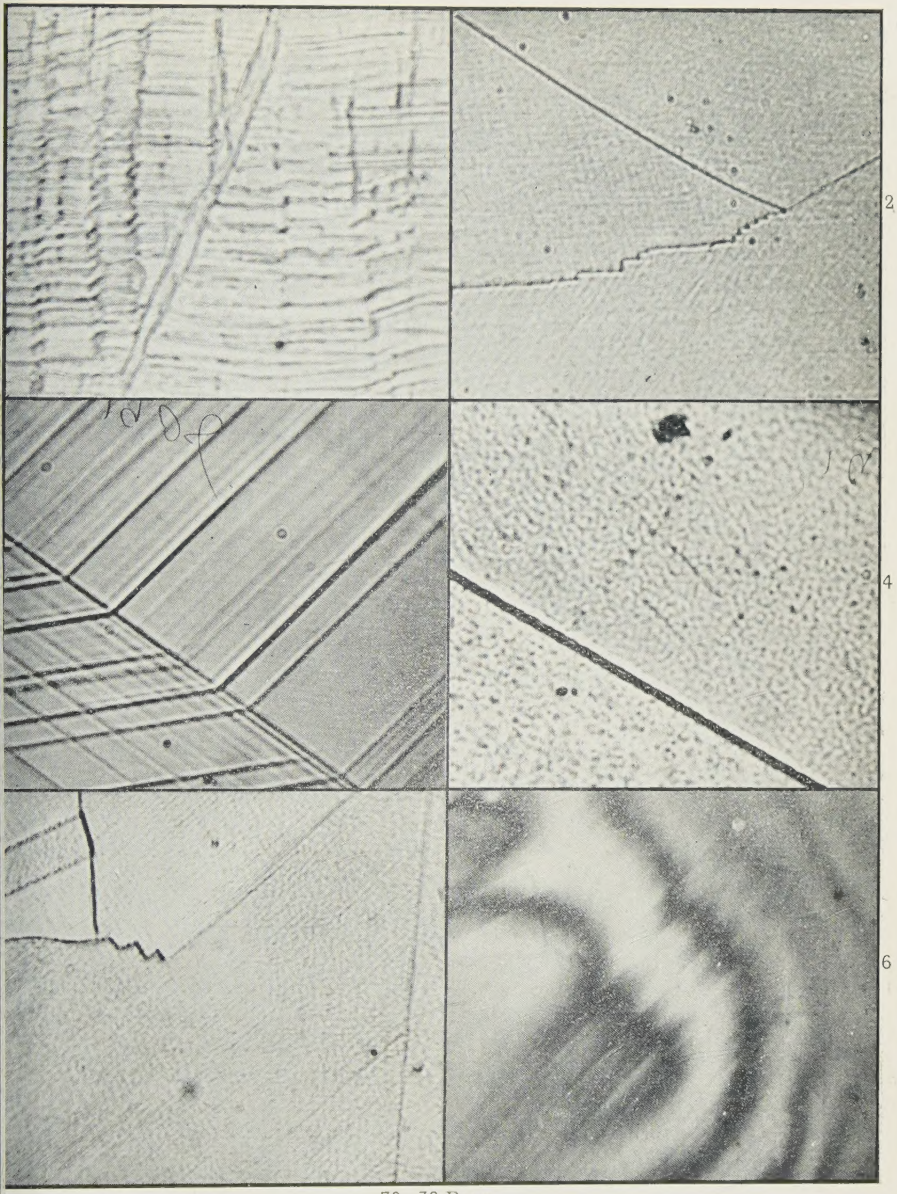
### 4. *Connection Between Striations and Crystallographic Orientation of the Plane of Polish.*

In all specimens examined and at all deformations some crystals could be seen containing no striations, although on the polished surface no crystals were free from slip lines at high deformation. Whether striations are revealed or not may depend on the crystallographic orientation of the plane of polish. It is perhaps significant that in Figs. 10 and 11 (Plate XVI), which were chosen at random, the angle between the two sets of striations is close to 60°. Since the slip planes of brass are the (111) planes, this angle would be obtained by sectioning along another (111) plane. Examination of other examples of two sets of striations showed a marked tendency for the angle of intersection to be close to 60°, 90°, or to be between 68° and 78°. These angles would be obtained by sectioning approximately along (111) (60°), (100) (90°), or (110) (71°) planes, respectively. It is possible, therefore, that only these planes etch suitably to reveal striations.

### 5. *Striations in Alloys Other than* 70 : 30 *Brass.*

Jacquet has observed similar markings in copper, as mentioned,[3] although in the present work they were not revealed in copper by a

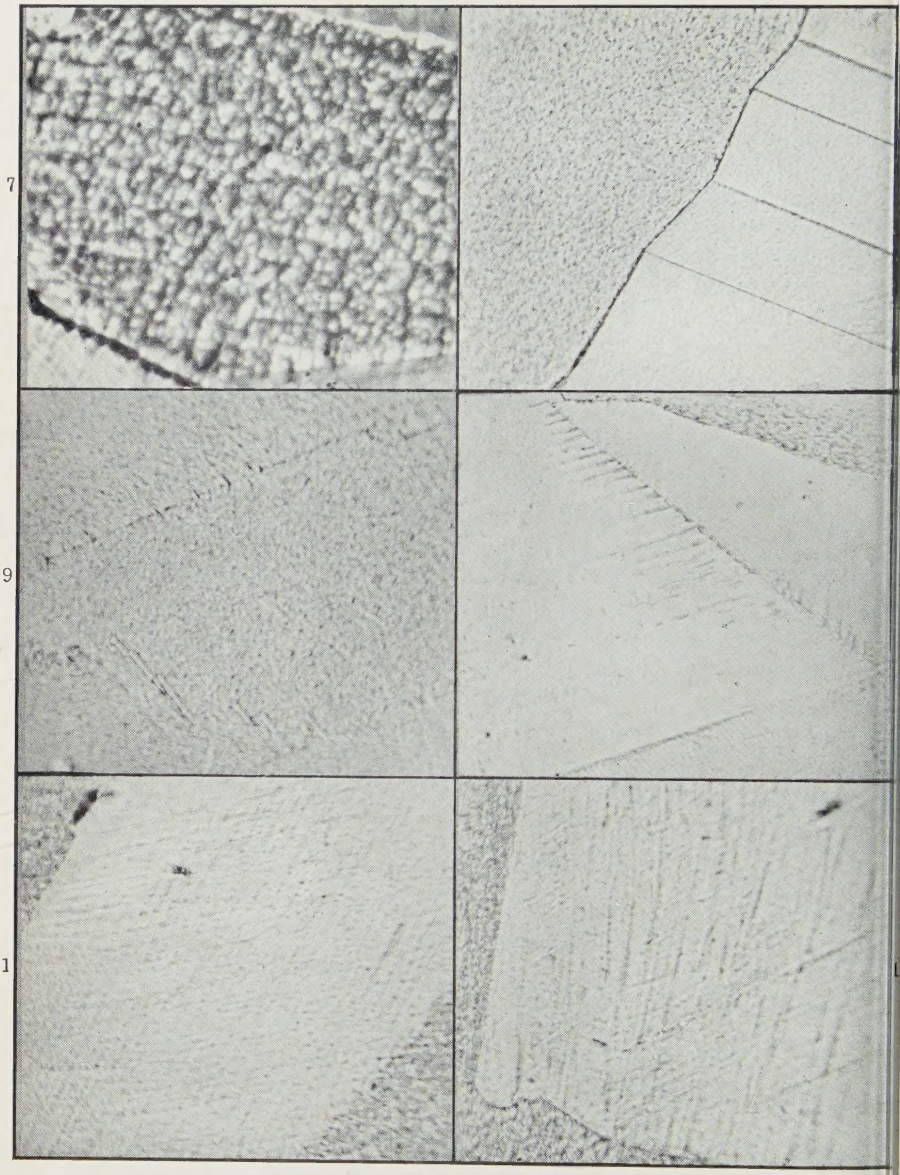
* i.e. the same plane within the limit of resolution by the microscope.



70 : 30 Brass.

FIG. 1.—Strain lines after 40% cold rolling, electrolytically etched. × 2000.
FIG. 2.—Striations after superficial deformation during preparation. × 750.
FIG. 3.—Slip lines after 4% deformation. × 1000.
FIG. 4.—Same area as Fig. 3, polished and etched, showing striations parallel to slip lines of Fig. 3. × 1000.
FIG. 5.—Striations after 4% deformation. × 1000.
FIG. 6.—Same area as Fig. 5 after further 4% deformation, under interference microscope. Slip lines parallel to striations of Fig. 5. × 1000.

[*To face p.* 98.




70 : 30 Brass.

FIG. 7.—Striations after 8% deformation. Electron-microscope reproduction. × 7500.

FIGS. 8–12.—Striations in tapered tensile specimen. × 1250.

FIG. 8.—0% elongation.
FIG. 9.—¼% elongation.
FIG. 10.—3% elongation.
FIG. 11.—9% elongation.
FIG. 12.—35% elongation.

copper ammonium chloride etch. Nor could they be detected in zinc (99·99% pure), although several reagents were tried. They were, however, very prominent in copper–tin and were more prominent in antimonial 70 : 30 brass than in pure brass.

A range of brasses was examined. Alloys of nominal copper : zinc ratios of 90 : 10, 80 : 20, 70 : 30, and 60 : 40 were cast and forged. Annealed and furnace-cooled specimens ascertained to be free from striations were reduced about 4% by hammering, and polished. After etching in copper ammonium chloride solution, striations were much more prominent in the 60 : 40 alloy than in the 70 : 30, and faded with increasing copper content to become invisible with 90%. After repolishing and etching in hot dilute orthophosphoric acid, the position was approximately reversed; striations were more prominent in the 90 : 10 alloy than in the 60 : 40.

## III.—Nature of Striations.

An electron-microscope photograph (Fig. 7, Plate XVI) of a 70 : 30 brass deformed 8% shows more detail than the optical-microscope photographs. The heavy striations are presumably those observed with the optical microscope; in addition many finer ones can be seen. The average fine spacing is about 0·2 $\mu$, which is the order of magnitude usually given for mosaic blocks. Bearing in mind also the cellular structure in Fig. 7, it may therefore be that striations represent a row of mosaic junctions, coinciding with slip planes, which for some reason etch heavily.

The most probable reason is the setting up of strain by the slip, but there are two other possible reasons : (*a*) the existence of composition fluctuations similar to those found by Daniel and Lipson,[5] and (*b*) precipitation of β-brass along slip planes. (*a*) was tested by preparing two further tapered tensile specimens, annealing at 750° C., furnace-cooling one and water-quenching the other, and then proceeding as described in an earlier section. The incidence of striations was the same in both specimens. Since the 750° C. anneal would be expected to obliterate at least partially any composition fluctuation, and since this obliterated state would have been retained in the water-quenched specimen, it seems reasonable to conclude that (*a*) does not apply. Consideration of the results obtained with the brasses of 90 : 10 to 60 : 40 copper : zinc ratio, described in the preceding section, suggests that (*b*) does not apply either; for if it did, the striations would be at least as prominent in 90 : 10 as in 60 : 40 brass with both of the etching reagents tried, because of the greater difference between ground-mass

and precipitate in the former alloy. It is therefore concluded that striations are probably regions of strain.

The first signs of striations appear at grain boundaries (Fig. 9, Plate XVI). This is to be expected, since slip in the adjoining crystal combined with grain-boundary irregularity presumably reduces the likelihood of atoms in the slipped plane near the grain boundary gaining correct lattice positions at the end of glide, so that the lattice becomes strained in these regions sooner than elsewhere.

Presumably the regions of strain revealed by striations account for some of the work-hardening during deformation. Since the striations are patchy, it follows that work-hardening of a given slipped plane is non-uniform over the area of the plane; and since the striations become longer and more pronounced with increasing external deformation, within limits, it seems reasonable to conclude that, when a plane that has already slipped slips again,* fresh areas of it are work-hardened. Repeated slip on the same plane * seems to occur without any obvious limit, but, since striations appear never to traverse an entire crystal, apparently does not succeed in work-hardening the entire plane.

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* i.e. the same plane within the limit of discernment of the microscope.